

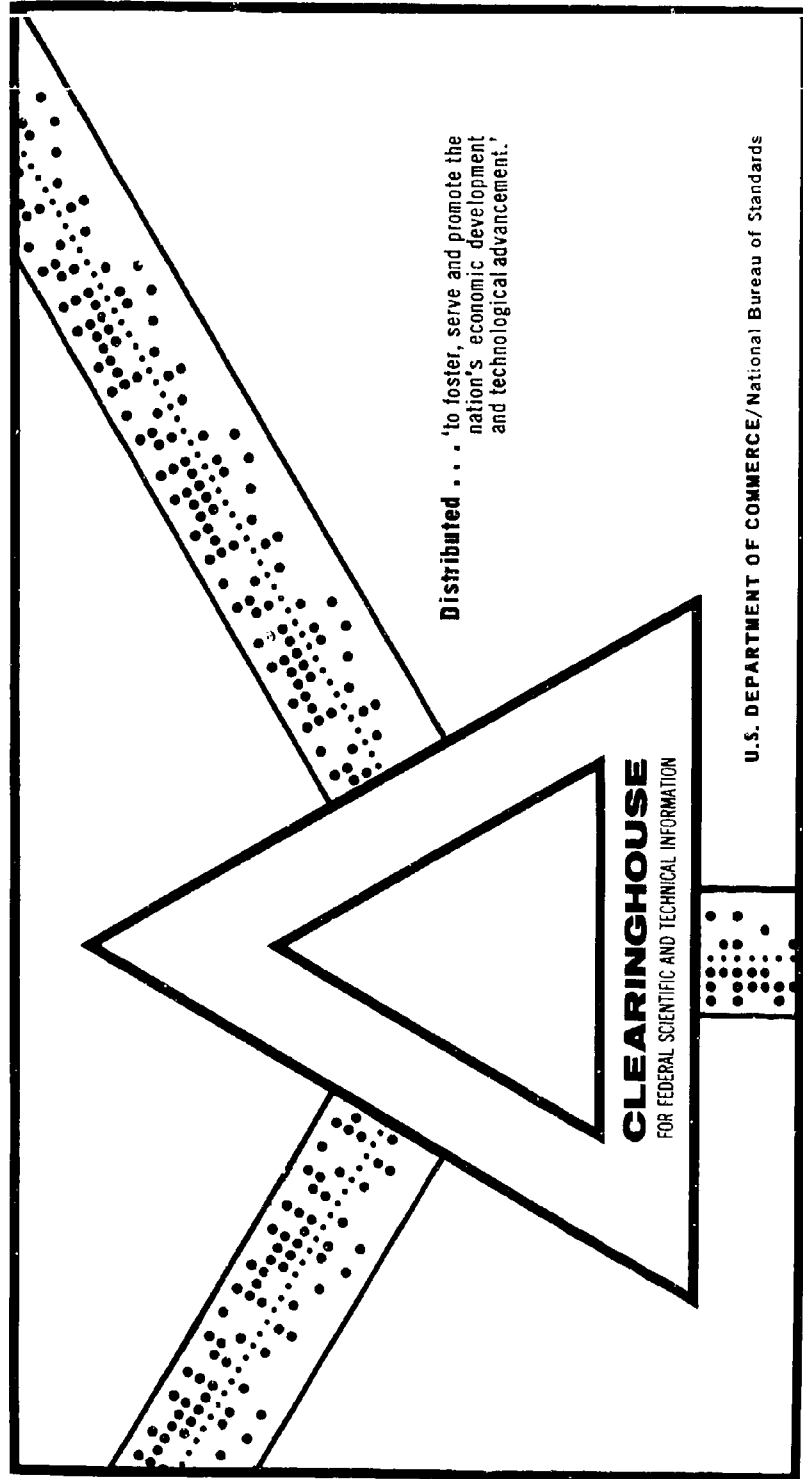
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PROCEEDINGS OF THE U. S. ARMY NATICK LABORATORIES FLASH
BLINDNESS SYMPOSIUM, 8-9 NOVEMBER 1967

John M. Davies, et al

Armed Forces-NRC Committee on Vision
Washington, D. C.

November 1967



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Proceedings of the
U.S. Army Natick Laboratories
FLASH
BLINDNESS
SYMPOSIUM

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Proceedings of the U.S. Army Natick Laboratories
FLASH BLINDNESS SYMPOSIUM

8-9 November 1967

Edited by
John M. Davies
David T. Randolph

Armed Forces—NRC Committee on Vision
Washington, D.C.

FOREWORD

Dr. William Benson, NAS-NRC Committee on Vision, Washington, D. C.

This symposium was held under the auspices and supervision of the Advisory Board on Military Personnel Supplies of the National Research Council with the cooperation of the Natick Laboratories.

Recognizing that a major portion of the speakers and those in attendance at the symposium are members of the Committee on Vision of the National Research Council and that the subject of the symposium would be of general interest to the community of visual scientists, the Executive Council of the Committee voted to publish the proceedings of the symposium for the benefit of its membership.

Proceedings of a symposium on the current state of knowledge in flash blindness technology with emphasis on the military application of this technology.

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Foreword

Dr. John M. Davies, Pioneering Research Laboratory, US Army Natick Laboratories, Natick, Massachusetts

The purpose of this symposium was to arrive at an understanding of the state of knowledge in flash blindness technology, with the underlying aim of determining how this information could or should be applied to military problems. It seemed desirable and necessary to assemble people who have been working in this field so that they could present their recent findings and discuss the meaning of the results now available.

In arranging any conference, there are conflicts with other events, and compromises must be made to arrive at a suitable date. In our case this seemed to be particularly difficult, and finally we had the choice of a conflict with a NATO meeting, or a rather indefinite postponement. We are sorry that the date selected did not allow some people interested in this work to attend. In one sense the date selected was especially appropriate. The Nobel prize in medicine and physiology had just been awarded to three people who have spent their working lives in vision research- to Dr. Ragnar Granit and Dr. H. Keffer Hartline for their studies of the electric potential generated in the retina by light, and the resulting currents sent along the nerve to the brain; and to Dr. George Wald for his studies of chemical reactions in the retina, including the optical absorption and the bleaching characteristics of retinal pigments. The electroretinographic potential (ERG) provides the basis for measurement of flash blindness in many experiments, especially with animals, and knowledge of the chemical reactions provides the basis of our understanding of the mechanisms involved in flash blindness.

Considering the use of light as a weapon, the eye is among the most vulnerable targets. The cornea and lens of the eye may be damaged in

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various ways by exposure to intense light, but the most critical visual component is the retina. Injury to the retina may take the form of retinal lesions; the effect of the injury then will depend partly on the location. Small lesions may cause very little decrement; if on the fovea, the loss of vision may be nearly complete. Even if not on the fovea, a severe chorioretinal lesion may allow blood to flow into the vitreous body; this type of blindness may be temporary. These effects may be extremely serious; but in this symposium the concern was not directly with them, but concentrated upon the temporary degradation of vision caused by bleaching of the visual pigments, such as rhodopsin and cyanolabe, chlorolabe and erythrolabe, and the effects that may follow that bleaching. Several people have indicated their dislike of the use of the term flash blindness in this connection, feeling that it is not real blindness, but only a temporary lowering of visual sensitivity; however, a better term has not been suggested. Many studies have been made of the decrement of visual functions following exposures to relatively low-intensity light, generally described as dark or light adaptation. These studies were the precursors of present flash blindness research which is concerned with brief exposures to extremely high-intensity photic stimuli. Adaptation does not seem a sufficiently broad term for these studies, and for this symposium the term flash blindness will continue to be used.

Perhaps our position at Natick Laboratories needs to be clarified. The development of weapons is not within our mission; but providing protection against weapons, especially for the individual soldier, is a major function of these laboratories. To develop that protection we need to know about the hazard in detail. We need to know the effect of various factors that influence the production of flash blindness; the

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intensity and duration of the flash, the related quantity of energy, and the wavelength, as well as the conditions of the eye relative to the stimulus. Very likely the needs of other Department of Defense agencies are exactly the same. Of perhaps the most interest is the maximum duration of flash blindness that can be produced, and related to that, the maximum duration that can be produced without also causing permanent injury. Along with these specific data we need to understand the mechanisms involved in flash blindness in as much detail as possible.

In recent flash blindness studies, rather short-duration blinding flashes have been used, sometimes as short as the microsecond range, but now even shorter pulses are available. Lasers with pulse durations as short as perhaps 30 nanoseconds have been used to produce retinal lesions. Apparently these devices have not been used to produce flash blindness. This, we feel, will be the next step in flash blindness research.

Another phase of the symposium needs specific mention. A part of it was concerned with eye protection; the discussion was based primarily upon classified information and will not be included in the written summary. We would like to express our appreciation to those who helped in the preparation of these discussions. We wish especially to thank Willard L. Derksen of the Naval Applied Science Laboratory, in Brooklyn, for his participation, and for his permission to reproduce the table on the last page of these proceedings. Special thanks are also due to LTC Edward Blackburn of DASA, CPT David Anderson of the Night Vision Laboratory, Ft. Belvoir, Va., Mr. Donald I. Promish of the US Naval Air Development Center, Johnsville, Pa., Mr. Ennis F. Quigley, US Army Nuclear Defense Laboratory, Edgewood, Md., and CPT Kurt Bauermeister, Brooks AFB, San Antonio, Texas.

FLASH BLINDNESS AND THE MISSION OF NATICK LABORATORIES

Dale H. Sieling, Scientific Director
U. S. Army Natick Laboratories, Natick, Mass.

On behalf of the personnel at Natick Laboratories I would like to welcome you to this symposium and describe our mission to you. Natick Laboratories has been given the responsibility by the Department of the Army to create and develop protective systems for the combat soldier. These systems include devices to protect him against any kind of natural or imposed hazard. The advent of new light producing devices has given us an added responsibility for producing various systems that will protect the combat soldier from any device that might be invented or developed using light as the weapon.

As you know, for the past two or three days they've had some rather large demonstrations in the Soviet Union to commemorate the 50th anniversary of the 1917 revolution. I was talking to one of my fellow scientists at one of the other laboratories yesterday and he said that he had noticed the television accounts of the Moscow celebration. The new gadgets that were being shown over there contained a number of night vision devices which could be identified by simply looking at the equipment as it passed. I'm sure that with the sophistication of the scientific community in the Soviet Union, all types of light producing devices, either for offensive or defensive purposes, have been completely studied.

Therefore we regard your conference here at Natick Laboratories on the impact of flash blindness on the visual system as extremely important. We hope that we can extract from this conference a guide line for what we should do in the future to develop protective systems for the combat soldier against any kind of light producing instruments. I know there are certain people who have a "Buck Rogers" imagination, and who feel that some time in the future we'll have rays of various kinds that would either incapacitate, wound or kill soldiers. Your studies of the mechanisms of flash blindness should be of such a nature

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that we as protective system developers can utilize this information. This must be done in such a way as to ensure that the protective systems we develop are adequate for any kind of system that might be employed by an enemy or potential enemy.

I might say that sometimes what we do to produce these devices doesn't always work out the way we thought it would. For example, one of our responsibilities here at Natick Laboratories is for printing devices that are used in the production of propaganda leaflets. These leaflets are used in warfare to convince the enemy that he should not continue to fight but should surrender. I read in the New York Times a few weeks ago that the Americans had showered 250,000 leaflets on a town with a population of 70, near the DMZ in Vietnam. I thought this was at least adequate to do what it was supposed to do but I subsequently heard that shortly after the inundation of this town with leaflets, the Viet-Cong leader from that neighborhood surrendered. Of course the Americans were very much interested in what led him to the decision to surrender, so he was interrogated by the G-2, or the intelligence community, to find out what it was that had happened recently that had caused him to surrender. He said it was those leaflets. This of course brought the interrogator to attention, and through an interpreter he asked, "Well, what was it in these leaflets that caused you to surrender?" "Oh", the Viet-Cong said, "It wasn't what I read, it was the fact that I had to pick them up".

Well, sometimes intentions go awry, but I hope that in your conference here you will bring to us the latest useful information which has a direct bearing on our problems. I am sure this conference will be extremely useful to those of you who are trying to solve the problem of flash blindness and to those of us who must use your solutions. Thank you very much.

RECOVERY FROM SHORT FLASHES OF LIGHT APPLIED
AT VARIOUS LEVELS OF DARK ADAPTATION

Ernst Wolf
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Flash blindness is a term used to describe the decrease in visual function following sudden or prolonged exposure to high luminances. The effects may vary from a fraction of a second to several minutes with no permanent loss either in visual acuity or the subject's capability of re-adapting to low luminances. Permanent loss of vision may occur from exposure to electric arcs, the sun, and atomic explosions^{1,2,3,4,5,6}.

Permanent loss of vision due to damage of the retinal receptor cells, the pigment epithelium and the ganglion layers of the retina, have been described in detail on the basis of ophthalmoscopic and histological examinations^{7,8,9,10,11}. In some cases, various degrees of temporary or permanent loss of vision, not associated with visible recognizable changes in the retinal structure have been shown to occur and have been associated with chemical changes in the structure of the photosensitive pigments (retinal proteins) of the receptor cells^{12,13,14}.

Transient or permanent damage to the retina depends to a large extent on the amount of radiant energy reaching the retina and the locus of impact. A retinal lesion of small angular subtense when situated in the center may cause a scotoma serious enough to render an eye blind, reducing the resolving power of the eye far below the level necessary for fine discriminations. The same size lesion located extra-foveally might be completely ignored and present no handicap to vision.

The studies presented in this paper are concerned with temporary vision loss produced by luminances far below levels which would cause permanent damage. The recovery of sensitivity attained prior to a blinding flash at various levels of adaptation is investigated in the scotopic, mesopic and photopic range of vision.

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In studying dark adaptation, the customary procedure is to expose one or both eyes to a light source of known luminance for a definite length of time; then determine at intervals for one or both eyes the amount of light required to yield a response threshold until no further increase in sensitivity occurs. Thus, a dark adaptation function is obtained which correlates threshold luminance and time. This curve shows two segments, differentiated from each other by a rather sharp break. The upper, earlier segment, is ascribed to the adaptation of the cones; the lower later segment, to the adaptation of the rods¹⁵.

The cone part describes the photopic, the rod part the scotopic range of vision. The transition point, or break, is by no means fixed, and may shift on the log luminance scale as much as 1.5 log unit and along the time axis several minutes depending upon (a) the luminance of the pre-exposure source, (b) the duration of pre-exposure, (c) the retinal area exposed, (d) the spectral characteristics of the pre-exposure light, (e) the size of the test field, (f) the location of the test field on the retina, (g) the duration of the test flash, (h) the criterion for target recognition, and (i) the spectral composition of the test light^{16,17,18,19,20}.

The course of dark adaptation is therefore a result of a multi-varied system, and a "standard" dark adaptation function exists only under a specific set of conditions. A change in any of the above parameters alters the shape of the composite curve or one or the other of the two segments. The evaluation of night visual efficiency, on the basis of dark adaptation tests must therefore depend largely upon the methods employed. The major question that arises in the

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evaluation of visual performance in dark adaptation is whether the lowest threshold level is actually a valid measure, since the eye is seldom required to function at this sensitivity level. Thus, the capability of regaining a given sensitivity level after a sudden disturbance of the stationary adaptive state, rather than the attainment of maximal sensitivity in time, is probably of greater importance.

If, for instance, the eye has been exposed suddenly to the glare from headlights of an automobile at night, recovery from this exposure is much faster than the time required for gaining maximal sensitivity of the retinal elements. Exposure of the eye for a prolonged period of time to either a moderately intense source or to a short intense flash will have very different effects upon the rate of dark adaptation. In the first case, it must be assumed that the photo-sensitive pigments of the retinal elements are decomposed by light into various fractions, and that the subsequent recombination of the constituents in combination with new materials requires a considerable length of time. In the second case, the short flash produces only an imbalance of the prevailing stationary condition which may be regained comparatively quickly. This fast phase of recovery of sensitivity at specific levels of adaptation is the object of the present investigation^{21,22,23}.

METHOD

Before dark adaptation measurements were made, the eye was pre-exposed to white light providing an even illumination over a 40° visual field. The luminance was 1500 millilamberts as measured by means of a Macbeth illuminometer at eye position. At the completion of pre-exposure, the observer shifted to a visual discriminometer²⁴

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and fixated a red point presented through the left beam of the double beam system of the instrument (Fig. 1). The right beam served for presentation of the test field. By means of quadrilateral slits (S_1) the test field was adjusted to a square whose sides subtended a visual angle of 2° , and it was placed in the nasal field, 7° from fixation. A photographic slide of equally spaced black and white bars was fitted into the square opening. The 2° test field showed 4 white and 3 black bars, each subtending an angle of approximately 17 minutes. The test field was presented for .04 sec through the shutter (K_1). The observer responded to each presentation by indicating whether he was able to see the striation. The experimenter changed the position of the neutral density wedge in the light path (W_1) for each presentation, until a point was reached at which the striation was barely perceptible and at which a small shift of the wedge to a greater density did not elicit a response. For each end point the time from cessation of light exposure and the wedge position were recorded. Measurements were repeated at intervals of 1 to 2 minutes until after 30 minutes no significant further increase in sensitivity was noticeable. Plotting in the conventional manner, log threshold luminance against time in the dark, typical dark adaptation curves were obtained.

After 30 minutes a flash was presented through the left arm of the discriminometer. The light from an H-5 mercury vapor arc was sent through the system focusing collimator L_5 on the quartz capillary. The wedge (W_2) was removed and the slits (S_2) were wide open so that the flash illuminated a circular field subtending 40° as seen through the telescope. The luminance was 11,000 millilamberts. The shutter (K_2) controlled the duration of the flashes.

The velocity of adaptation after a brief flash was so fast that

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the customary method of determining dark adaptation thresholds could not be employed. Instead, it was necessary to set successively the wedge at several predetermined luminances and measure the time at which the striation became visible to the subject, when the field was presented each second for .04 sec. Measurements were made in several steps, until the test field luminance equaled the threshold level of the preceding dark adaptation run. Thus the rate of recovery was followed and the total time for recovery from the flash was determined. Adapting flashes of 0.1, 0.2, 0.5, 1.0, and 2.0 seconds duration were presented.

RESULTS AND DISCUSSION

The results obtained by these methods are presented for two subjects. Figs. 2 and 3 show the data obtained from the right eye of MJZ and from the left eye of EW respectively. On the left are shown the dark adaptation functions obtained after 10 minutes pre-exposure to the 1500 millilamberts white light. On the right the data for the course of recovery to the original level of dark adaptation are shown. In each case, five settings for test field luminance were made, and the time was determined at which the striation of the test target became visible.

Comparison of the curves for the five flash durations show that the time for total recovery increases with flash duration. For MJZ (Fig. 2) recovery times for flash durations 0.1, 0.2, 0.5, 1.0, and 2.0 sec. are respectively 27, 36, 41, 55, and 103 sec. For EW the recovery times are 45, 50, 63, 72, and 127 seconds.

The recovery curves on the right of Figs. 2 and 3 are re-plotted in Fig. 4. Here the relationship between log threshold luminance and log recovery time is shown. As flash duration increases, the

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lines shift to greater log recovery time values. In the upper set of curves, the slopes of the five lines are approximately the same. The lower set of curves shows slightly steeper slopes as flash duration increases.

Since dark adaptation will proceed only to the luminance level of the environment, it is possible to study recovery at any desired level by choosing surround luminances in the photopic, mesopic, or scotopic range of vision.

The eye was again exposed to white light of 1500 millilamberts for 10 minutes. Three surround luminances (S.L.) were chosen; one which yielded a dark adaptation curve lacking the rod segment entirely (A), (S.L. = 3.96 millilamberts), a second which yielded a duplex curve in which the rod segment reached slightly below the level of cone-rod transition (B), (S.L. = .88 millilambert); a third surround luminance (.0043 millilambert) which permitted the rod segment to descend about half way to the maximal sensitivity level (C). For comparison, data are finally presented for tests without background illumination (D) (Figs. 5 and 6). When adaptation had reached a steady level, a flash was presented of 11,000 millilamberts with a duration of 0.5 sec. The resulting curves are shown on the right of Figs. 5 and 6.

The recovery curves for the surround condition in D of Figs. 5 and 6 correspond to those shown for a flash duration of 0.5 sec in Figs. 2 and 3. When dark adaptation was delayed by the presence of a background illumination which allowed the rods to reach one-half of their final sensitivity (Curve C, Figs. 5 and 6), or when the background luminance allowed only a small number of rods to function (curve B, Figs. 5 and 6), the corresponding recovery curves show a

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fast drop and reach their final level earlier as the level to which the eye has been adapted increases. When dark adaptation involves cones only, recovery is extremely fast (Curve A, Figs. 5 and 6).

Fig. 7 shows the relationship between log luminance and log recovery time for each of the surround conditions. The slopes of the lines increase as the background luminance decreases. Thus the relative rate of recovery increases as sensitivity approaches its maximum.

With this technique it was possible to study a second, more practical application of recovery from bright flashes of light occurring during night driving. The use of absorptive filters (tinted windshields) for the reduction of headlight glare was investigated²⁵. It is obvious that a tinted windshield with about 70 percent transmission will reduce the glare effect of oncoming headlights. However, the same absorption which decreases glare would also decrease the visibility of objects on the road.

A thirty minute dark adaptation level was obtained. Then the eye was exposed for .04 sec to the light reflected from a white surface subtending a visual angle of 50° horizontally, and 30° vertically, yielding approximately 370 foot-lamberts. The recovery curve was obtained with a 2° square test field located 10° below fixation and shown on the right of Fig. 8. The smooth recovery curve reaches the previously established threshold level in 40 seconds. In repeated tests, and at the exposure level used, fatigue became a major factor in the experiment and the procedure was revised. The modification consisted in choosing a luminance level of the test field which was 0.3 log unit above the 30 minute threshold. This luminance corresponds to twice the final level of the test field, or half completion of full dark adaptation^{26,27}.

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To simulate more accurately driving conditions, a second change in the experimental arrangement seemed necessary. In night driving not the entire visual field is flooded by the headlights of an auto, but two distinct sources of high luminance are seen. To approximate this situation in the laboratory, the light from a projector mounted above and slightly behind the observer was reflected into his eyes from two small concave mirrors while he fixated a point 6° to the right of the right mirror. In this situation the observer experienced a light flash (0.04 sec) which corresponded to the appearance of headlights at a distance of 100 ft. The luminance of each light was 28,400 millilamberts.

The target luminance was set at 0.3 log unit above the 30 minute threshold level, and four conditions were used: (a) no tinted windshield glass; (b) tinted windshield in front of the test light; (c) tinted windshield in front of the flash source; and (d) a tinted windshield in front of both test light and flash source. The mean recovery times were 26.7, 31.1, 23.9, and 27.3 seconds respectively. These results indicate that recovery times were essentially the same, whether the flash source and test target were viewed with or without a tinted windshield in the light path. Faster recovery was achieved when the luminance of the blinding flash was reduced, and recovery was delayed when the test object was dimmed by interposition of tinted windshield glass.

In a third study with a 1° test field presented 7° nasally by means of a visual discriminometer²⁴, either the course of dark adaptation was followed for 20 minutes or the 20 minute threshold was determined. Then the luminance of the test field was adjusted to a level .3 log unit above the 20 minute threshold. The observer then

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received through the viewing system of the test instrument a flash of 4500 millilamberts flooding a circular field of about 35° visual angle. The test field then was presented for .04 sec at intervals of one second until the observer was capable of seeing the test field. The test was repeated three times after sufficiently long intervals of rest between trials. Thus, the time of recovery after a flash was measured (Fig. 9).

Adjusting the background to a luminance of $\bar{3}.80$ log millilamberts and giving the observer sufficient time for adaptation, the luminance for recognition of the test field was determined as a just-noticeable difference. The observer then was presented with a bright flash for .04 sec, and recovery time was measured by repeated presentation of the test field at intervals of 1 sec.

Three other background luminance conditions were used. These were $\bar{2}.30$, $\bar{2}.80$ and $\bar{1}.30$ log millilamberts. These represented points on the dark adaptation curve slightly below, slightly above and one log unit above the cone-rod transition.

Thus differential thresholds were obtained at five levels of surround illumination. These are represented by the five circlets on the right of Fig. 9, and show the rate of recovery to a previously established state of adaptation.

The slope of the recovery curve is a function of the luminance and duration of the flash, the background test field luminance ratio, size, retinal position and exposure time of the test field. Under standard conditions of testing, the reproducibility of the recovery curve is high and abnormal conditions of the retina should yield differences in the slope of the recovery-time function. At present we are still in the process of standardizing our technique in order

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to study the effects of specific retinal disorders upon the rate of recovery from flash blindness.

In a recent review, Williams and Duggar²⁸ emphasized the necessity of correlating visual performance and age. Two major changes occur as a function of ageing. The first is the increased sensitivity to scotomatic glare as a result of changes in the transmissiveness of the dioptric media, especially the lens^{29,30}. A second change can be seen in dark adaptation and response to flicker indicated by a progressive decrease in sensitivity^{31,32,33,34,35,36,37}. This is assumed to be due not only to increased scatter of light in the dioptric media but also to changes in the metabolism of the retina^{33,38}.

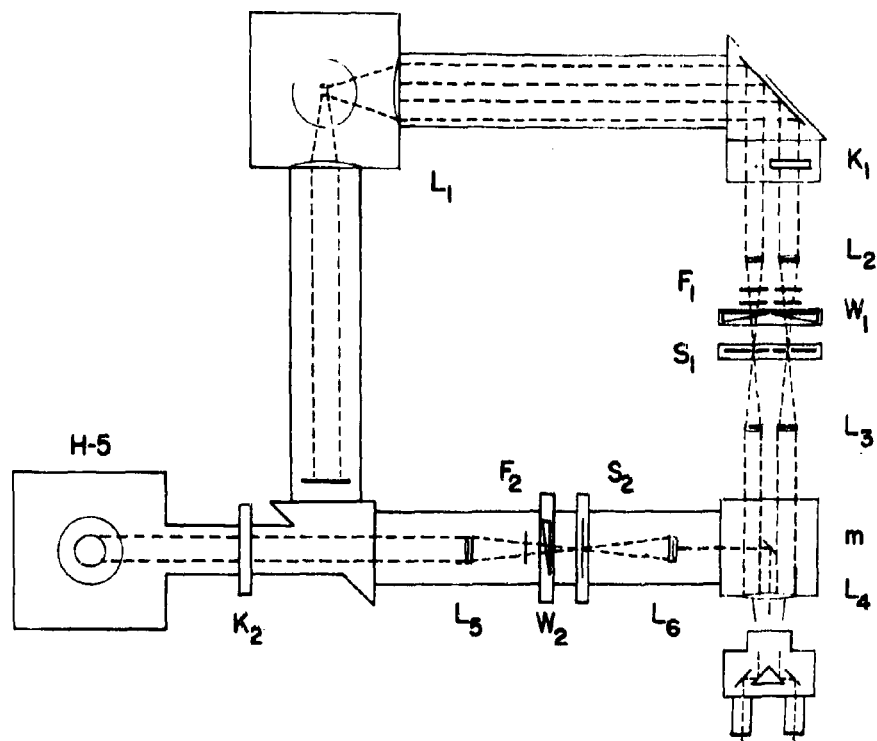
Thus, both physical and metabolic changes of the visual system which occur during the normal process of ageing will affect recovery from flash blindness. Scatter of radiation from a blinding flash in the lens may prevent local damage of the retina but will affect a larger number of retinal elements, increasing recovery time. Poorer retinal circulation might prevent heat dissipation and could conceivably result in an increased tendency toward retinal damage. Thus far we have little or no factual information. However, we know that in the clinical evaluation of psycho-physical data it is necessary to correlate observations with the age of the patient. Thus, it seems highly desirable when correlating flash blindness and recovery time data to consider the age of the individuals involved.

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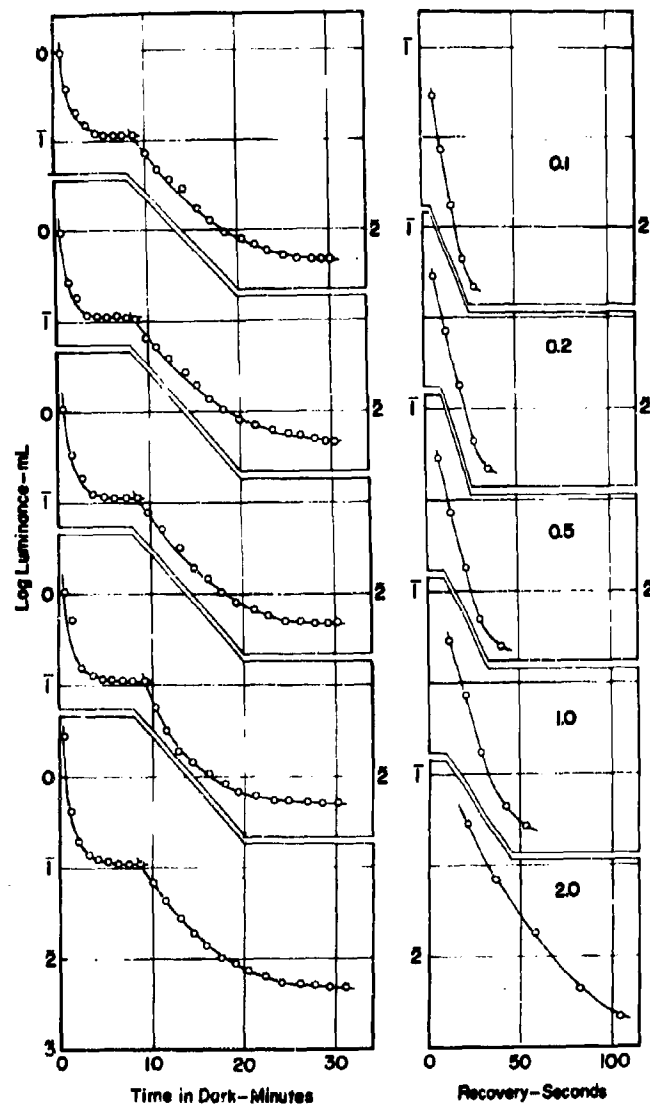
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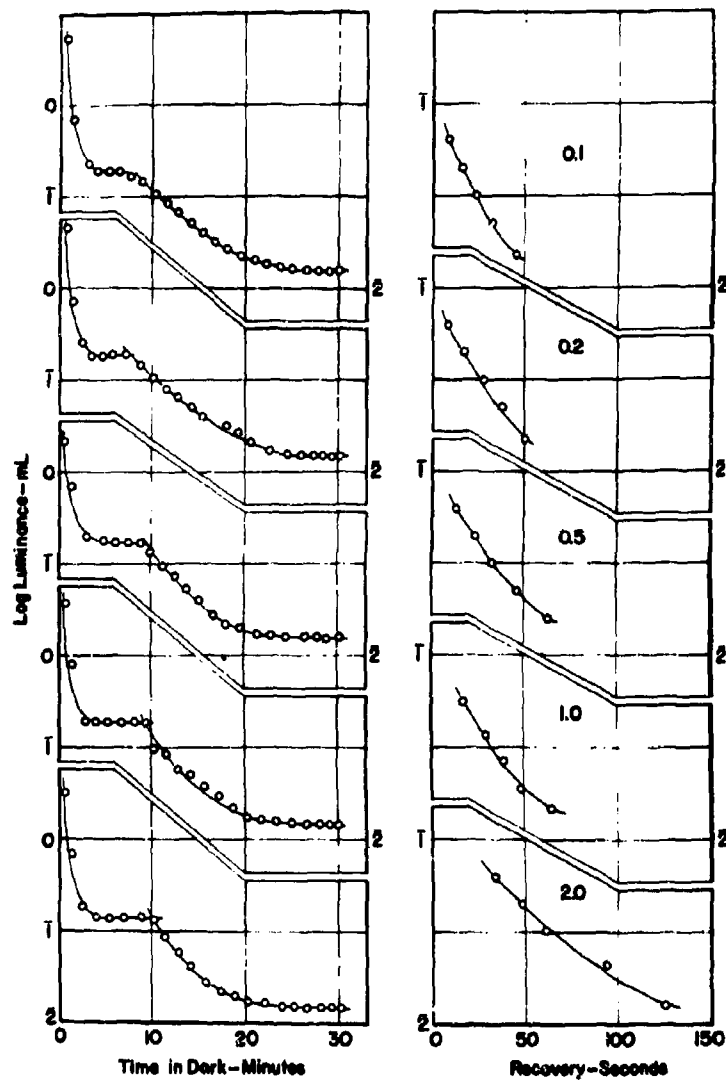
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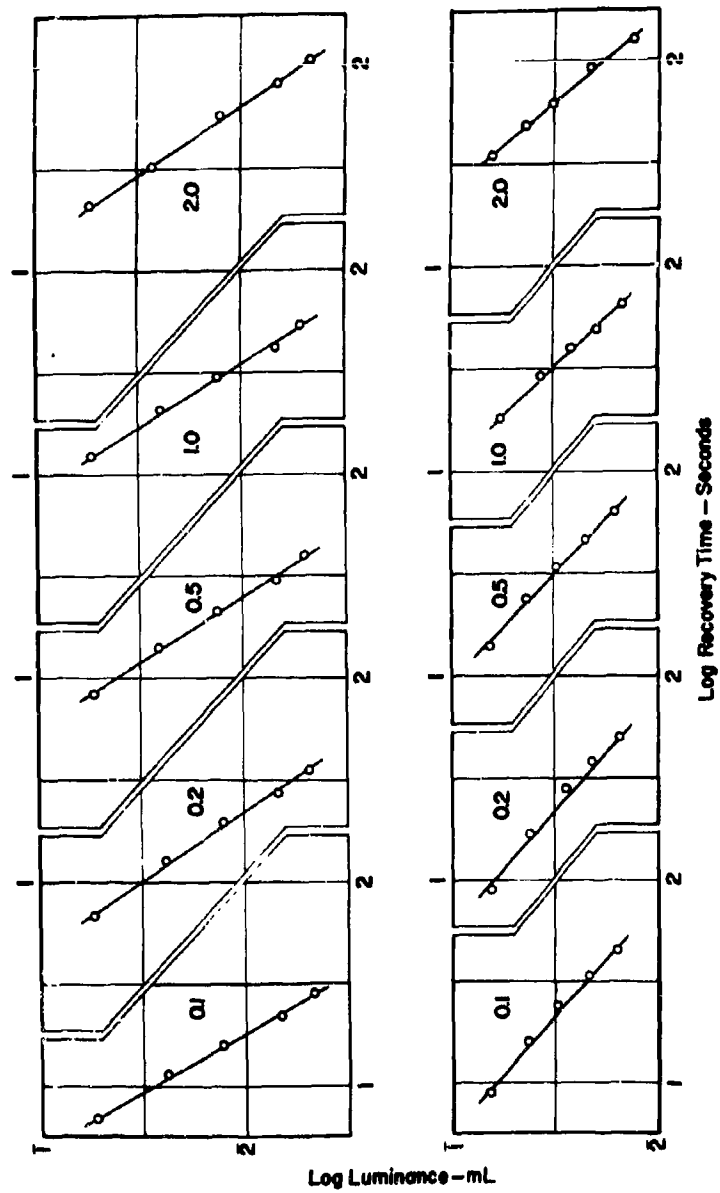
1. Diagram of visual discriminometer



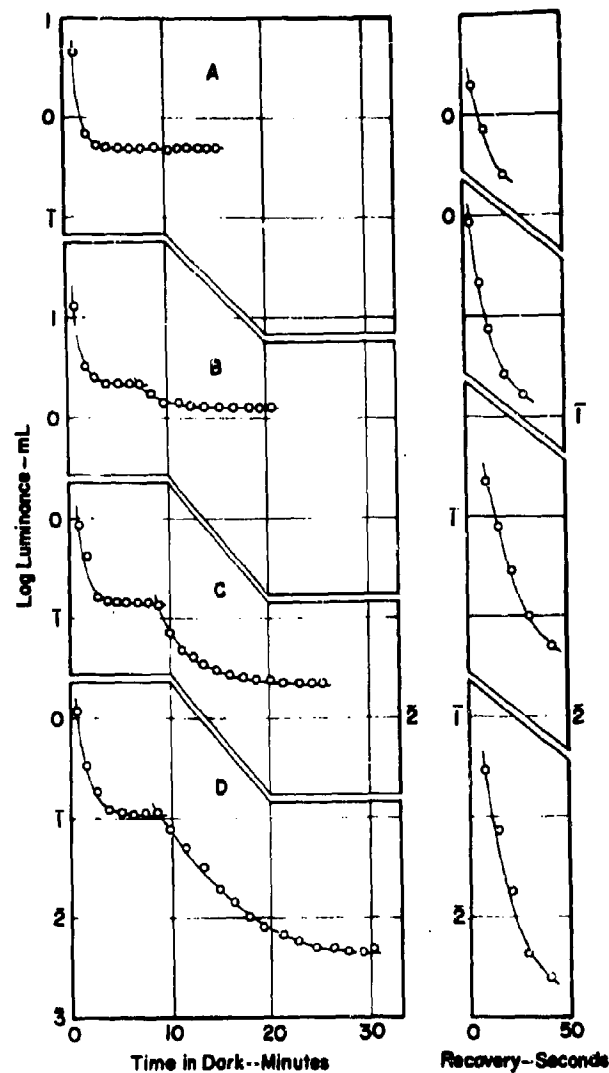
2. Dark adaptation curves obtained with 2° test square presented .04 sec. 7° from center in nasal field. Striation threshold. Pre-exposure 10 min. to 1500 mL. On right recovery curves after flashes of 11000mL and 0.1, 0.2, 0.5, 1.0 and 2.0 sec. Obs. MJZ.



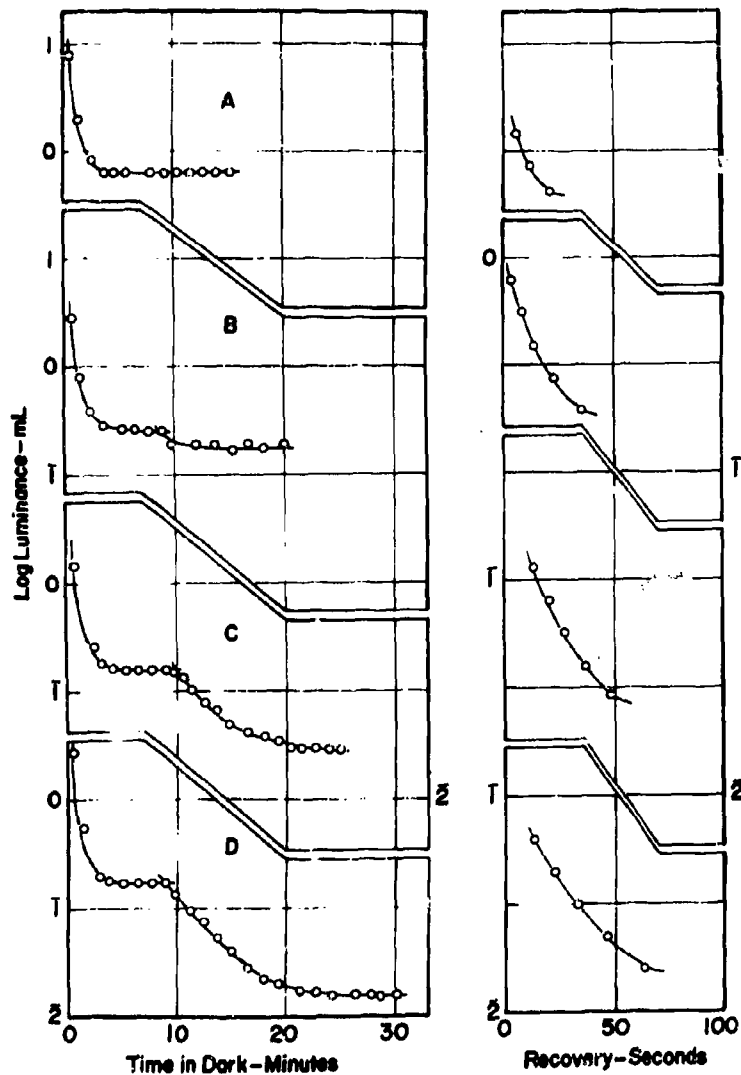
3. Dark adaptation curves obtained with 2° test square presented .04 sec. 7° from center in nasal field. Striation threshold. Pre-exposure 10 min. to 1500 mL. On right recovery curves after flashes of 11,000 mL and 0.1, 0.2, 0.5, 1.0 and 2.0 sec. Obs. EW.



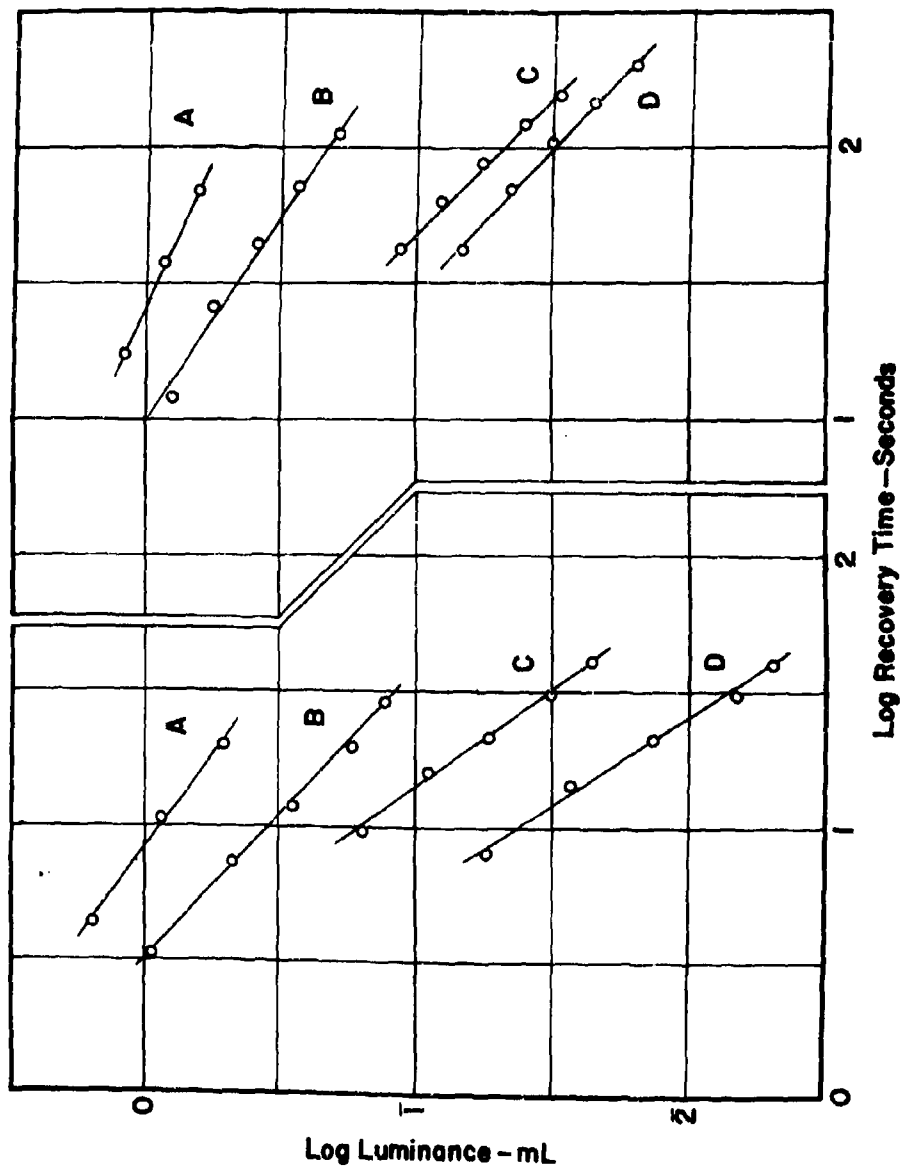
4. Relationship between log luminance and log recovery time when flash duration is 0.1, 0.2, 0.5, 1.0 and 2.0 sec. Top - MJZ, bottom - EW.



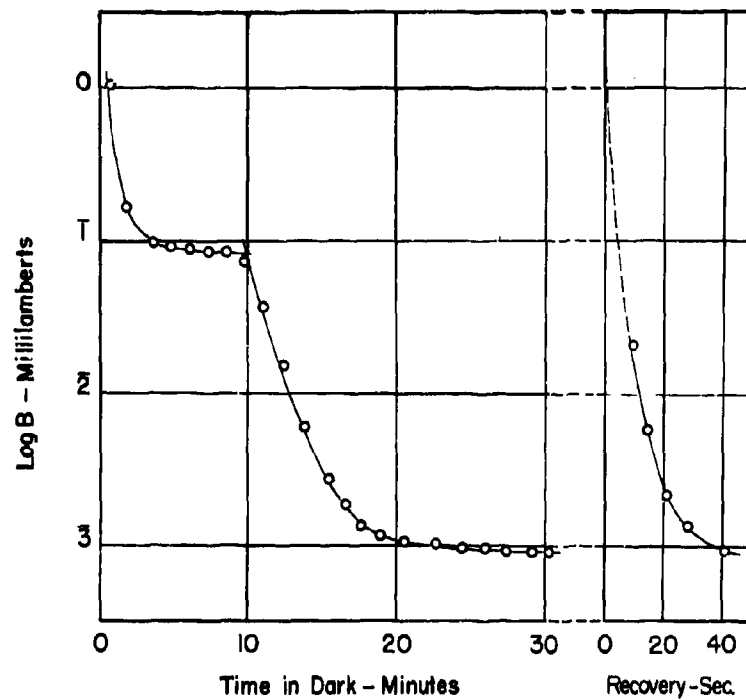
5. Dark adaptation curves obtained with 2° test square presented .04 sec. 7° from center in nasal field. Striation threshold. Pre-exposure 10 min. to 1500 mL. Surround luminance A = 3.96 mL, B = .88 mL, C = .0043 mL, and D = no surround. On right recovery curves after .5 sec. flash of 11,000 mL. Obs. MJZ.



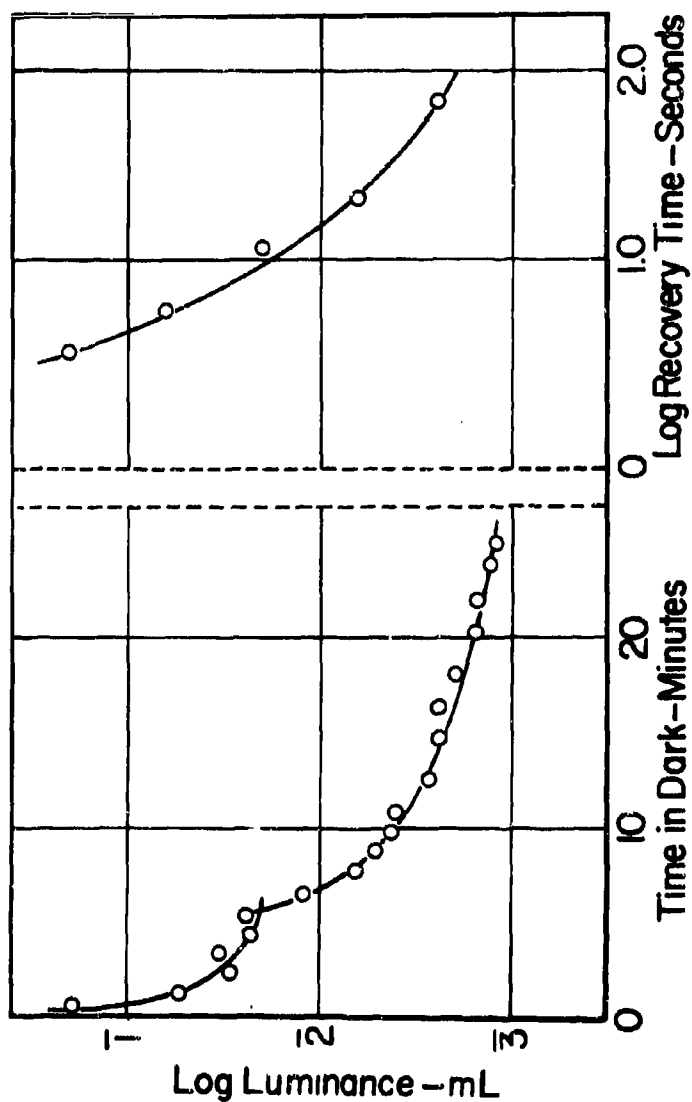
6. Dark adaptation curves obtained with 2° test square presented .04 sec. 7° from center in nasal field. Striation threshold. Pre-exposure 10 min. to 1500 m.L. Surround luminance A = 3.96 m.L, B = .88 m.L, C = .0043 m.L, and D = no surround. On right recovery curves after .5 sec. flash of 11,000 m.L. Obs. EW.



7. Relationship between log luminance and log recovery time when surround luminance is A - 3.96 mL, B - .88 mL, C - .0043 mL, and D - no surround. Flash duration 0.5 sec. Observers, MJZ - left, EW - right.



8. Dark adaptation curve obtained with 2° square test field presented 10° below center after pre-exposure to 1500 mL for 10 min. At right recovery from flash of .04 sec. reflected from white surface yielding 370 fl.



9. Dark adaptation curve obtained with 1° square test field presented 7° from center in nasal field after pre-exposure to 1500 mL for 3 min. On right recovery from flashes of light of .04 sec. duration and a luminance of 4560 mL, when surround luminance has been set for 5 levels. For details see text.

FLASH BLINDNESS AND THE POSITIVE AFTER IMAGE^{*}

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The human visual system is extraordinarily sensitive to small differences in luminance within the field of view. The normal individual will perceive a relatively small area differing by only two percent in luminance from the surround level, if he is adapted to the surround level. The key words in visual perception are adaptation level. If the average level of illumination in a visual field is suddenly altered, there is a period of changing sensitivity until the new level of adaptation is reached. Even relatively small changes in illumination level result in a period of adaptation. Several studies of the sensitivity of the eye during the transient period of adaptation have shown that there are two basic mechanisms responsible for the rapidly changing sensitivity. There is a neural effect and a photochemical effect.

Flash blindness is different in degree, not in kind, from any other kind of adaptation following exposure to increased light levels. In fact, it would be difficult to define precisely what is meant by flash blindness. Even the common experience of glancing out of a window at the bright sky and then looking down at work on a desk results in a short period of reduced visual sensitivity or in flash blindness. However, as the total amount of light flux entering the eye during a flash exposure is increased, a point is reached where a vivid after image of the flash source is perceived following the exposure. One is aware of the rapid fading of the after image during the period of readaptation to the preflash illumination level. Extensive work over the last few decades has confirmed that the after image is photochemical in origin.

Craik¹ was probably the first to demonstrate conclusively that

^{*}The research effort covered in this report was made possible through the support of the USAF School of Aerospace Medicine and the Defense Atomic Support Agency.

the after image was produced by events at the retinal level. He temporarily blinded the eye by pressure on the globe preventing the transmission of neural signals from the retina. While the pressure was applied, the eye was subjected to a bright flash which the subject could not perceive; but, when the pressure was removed and normal neural transmission restored, the after image was perceived. Subsequently, Rushton²⁻⁵ performed a series of experiments in which he measured the bleaching of the retinal photopigments in the living human eye and correlated the regeneration of the pigments with the change in increment threshold during dark adaptation.

In military operations, where personnel may be subjected to intense flashes of light, the problem of flash blindness takes on particular significance. It is not enough to know academically that the flashes bleach the retinal pigments and cause a veiling, bright after image to appear, but it is also necessary to know how much and how soon one can see after the exposure. It is common knowledge that large targets can be seen more quickly than small detail during dark adaptation. So obviously, the target parameters are important in stating visual recovery times. The total energy received by the retina during the flash is also a factor in the time of recovery. There is also the problem of whether one is looking around instead of through the after image to be considered. So, retinal position and size of the flash received are important parameters. The number of variables to be investigated in order to adequately describe visual recovery during flash blindness makes the task formidable. The one hope in solving such a complex problem is to look at the basic mechanisms in an effort to develop a predictive model for

estimating how much and how soon one can see.

For several years we have investigated the problems of visual recovery following brief, high-intensity flashes⁶⁻⁸. The primary effort has been directed toward an understanding of the mechanism underlying flash blindness in order to reduce the burden of the experimental determination of the effects of each of the variables. Figure 1 shows the basic apparatus used for the preliminary research at the School of Optometry of the Ohio State University.

The flash source was a 10,000 watt/second sun flash unit with a xenon-filled discharge lamp. A segment of the lamp was focused at the plane of the entrance pupil of the subject's eye to provide a Maxwellian view field of 10° diameter. Initially an enlarged image of the segment of the flash tube was focused on an aperture plate at A₁ filling the 20 x 10.5 mm aperture. A 48 inch telephoto lens L₂ collimated the light, and the rotating mirror M₁, the 20 inch telephoto lens L₃, and the aperture A₂, completed the shutter system. Light reflected from M₁ into L₂ was brought to a focus and swept past the aperture A₂ which was 4.1 x 4.3 mm. The ratio of the width of the image of A₁ and the width of A₂ determined the duration of the flash. The mirror was driven through a pulley system with five interchangeable combinations to provide speeds from 1820 rpm to 55 rpm, resulting in flash durations from 0.04 msec to 1.4 msec. The flash tube was triggered in phase with the mirror so that the tube reached maximum radiance at the instant that the image of A₁ reached the edge of A₂. This arrangement insured the same peak radiance for all flash durations.

The light from A₂ was reflected from a first surface mirror M₂,

through lenses L_4 and L_5 and was focused at a 1:1 magnification at the plane of the subject's pupil. A field stop A_3 at the focal point of L_5 provided a 10° flash field. The beam splitter B_1 reflected a portion of the flash to a first surface mirror M_3 where it was reflected into a phototube. The oscilloscope traces of the phototube signals were photographed for all flashes during the experimental sessions. Lenses L_6 and L_7 provided another Maxwellian view system with a 10° field. The field stop at A_5 was seen by the subject in the plane of A_3 and coincident with it after reflection from the beam splitter B_1 . A fixation target was placed at A_5 to aid in maintaining central fixation for the flash and the recovery targets.

Immediately after the flash, the mirror M_2 was swung out of the beam to the position shown by the dotted lines. The recovery targets at T_1 were transilluminated by the ribbon filament lamp at S_1 . Filters at S_1 controlled the luminance of the recovery targets. The lens L_4 imaged the target at a 2:1 reduction in the plane of A_3 where they were viewed by the subject with relaxed accommodation.

Figure 2 shows the spectral energy distribution of the xenon flash source relative to a tungsten ribbon filament at 3000° color temperature. The comparison was made through a series of interference filters at 24 narrow regions of the spectrum from 400 to 1100 m μ . The middle curve of Figure 2 is the steradiancy of the tube after filtering through a 3 mm thick KG-3 filter to remove the infrared. The filter was used during all experimental sessions. The luminance of the flash field with the filter was calculated from the steradiancy and the measured transmission of the optical system to be 4×10^5 I. at peak.

The time course of the radiance of the xenon flash discharge is shown in Figure 3. Portions of the flash could be chopped out by the shutter system for varying the actual durations of the flash exposure as shown in the figure.

In all of the experimental work, we have used Sloan-Snellen letters as recovery targets. This would appear to be an acuity measure as opposed to a simple detection measure. However, a pilot study showed that the general form of the recovery curves is similar for either a flashed disc of light or letter targets. The use of the letters does stabilize the increment thresholds by providing a forced choice situation. The subjects are encouraged to guess in identifying the letters, and the criterion of two correct responses in sequence has been adopted to avoid errors due to chance. Figure 4 shows a typical set of recovery time data for flash durations of one msec.

It would be an interminable task to measure the recovery times for every conceivable target of interest. Crawford⁹ showed how to generalize the recovery data for various target sizes and configurations from individual measures of a few types of targets. He defined an equivalent of background luminance as the luminance level of a superimposed bright field necessary for the threshold detection of the target. Figure 5 shows the results of an auxiliary experiment performed to determine the background luminance for two different sizes of the Sloan-Snellen target letters for various letter luminances. Figure 6 shows the results of expressing the recovery time data from Figure 4 in terms of the equivalent backgrounds. The two recovery targets now plot on a continuous curve which can

be used to predict recovery for other configurations if their equivalent background luminance is known.

The most dramatic perceptual effect of an intense flash of light is the lingering positive after image following the flash, and it is tempting to believe that it is the controlling factor in the rapidly changing threshold following the flash. The basic apparatus was modified according to the diagram in Figure 7 to measure the instantaneous brightness of the after image. The modification provided for either monocular or binocular matching of the after image with an external field. A pair of circular neutral density wedges F_1 were crossed to produce a uniform density sector that could be varied to attenuate the light in the matching field over eight log units. The circular wedges were mounted in gears and driven by a reversible motor. The motor unit had a solenoid-operated driving gear which retracted as soon as the power was interrupted so there was no overdrive of the wedges after the subject opened the switch. A rocker-type switch was mounted below and to one side of the bite plate so the subject could operate the switch with his fingers while he rested his hand on a solid support. The switch allowed instant reversal of the motor if the wedges were overdriven. The gear ratio was selected to insure that the density of the wedges could be changed faster than the anticipated drop in the after image brightness. A 1.0 density step could be achieved with the motor running for 2.6 seconds. The density of the wedges was continuously recorded as the subjects maintained a photometric match. Calibration of the wedges and recording drive allowed the density, and hence the field luminance, to be plotted as a function of time following the flash.

The source for the matching field was a standardized ribbon filament lamp run at 18.0 amps. The filament was imaged on a 2 mm circular aperture at A_1 which was imaged at a 1:1 magnification in the plane of the subject's pupil by the lenses L_1 and L_2 . For monocular matching the light path was as shown by the solid lines in Figure 7. The additional components shown by the broken lines were added for binocular matching. The filament was then imaged in the plane of the entrance pupil of the left eye to provide the matching field with the after image in the right eye. The field stop at S_2 was adjustable so the image could be made to coincide with that of the flash field stop at S_1 . Masks were inserted at S_1 and S_2 for various configurations of the photometric field. The configuration used in the two cases is shown by the inserts in Figure 7.

The task was not a simple one for the subjects, due to the flight of colors in the after image which required heterochromatic matching. The consistency in the results, however, was truly remarkable. Figure 8 shows three traces from three successive flashes for one subject. There is some variation, but the agreement was greater than might have been anticipated from the subjects' complaints about the difficulties inherent in the task. Figure 9 shows the average data from the brightness matching for the monocular, bipartite field condition for six subjects for two flash levels.

Figure 10 shows the relationship between the recovery time data and the instantaneous after image brightness. The data points from the after image matching are the solid dots. They are the group averages for six subjects. The solid triangles are the mean recovery time data for the same six subjects for the 28' letter.

The equivalent background luminance is precisely the same as the instantaneous after image brightness.

Large individual variations occurred in the after image brightness matching data; it therefore seemed advisable to analyze the data on an individual basis. The recovery times for two sizes of letters at luminances from 140 mL to 0.07 mL were predicted for each subject from his after image brightness-matching data and his equivalent field data. The procedure is shown graphically in Figure 11 for one subject for a 16.3' letter of 2 mL. The 84 predicted times for six subjects, 2 letter sizes, and 7 luminance levels were cross correlated with the measured recovery times. The correlation coefficient was 0.82. The effect of the bright 10° after image at each instant following the flash seems to have precisely the same effect on the foveal threshold as a steady external field of the same subjective brightness and size.

The simple relationship found between the equivalent background and the instantaneous after image brightness suggests that we may not have to investigate target parameters by subjecting subjects to bright flashes, but we can use external veiling fields corresponding to the range of after image brightnesses we expect to encounter. Now the problem remains of what range of after image brightnesses will be encountered.

One would hope that the earlier work relating the rise in increment thresholds to the amount of photopigment bleached by the flash would lead the way to a prediction of the brightness of after images following flashes of various durations and energy content. Rushton showed that the log of the threshold during recovery was

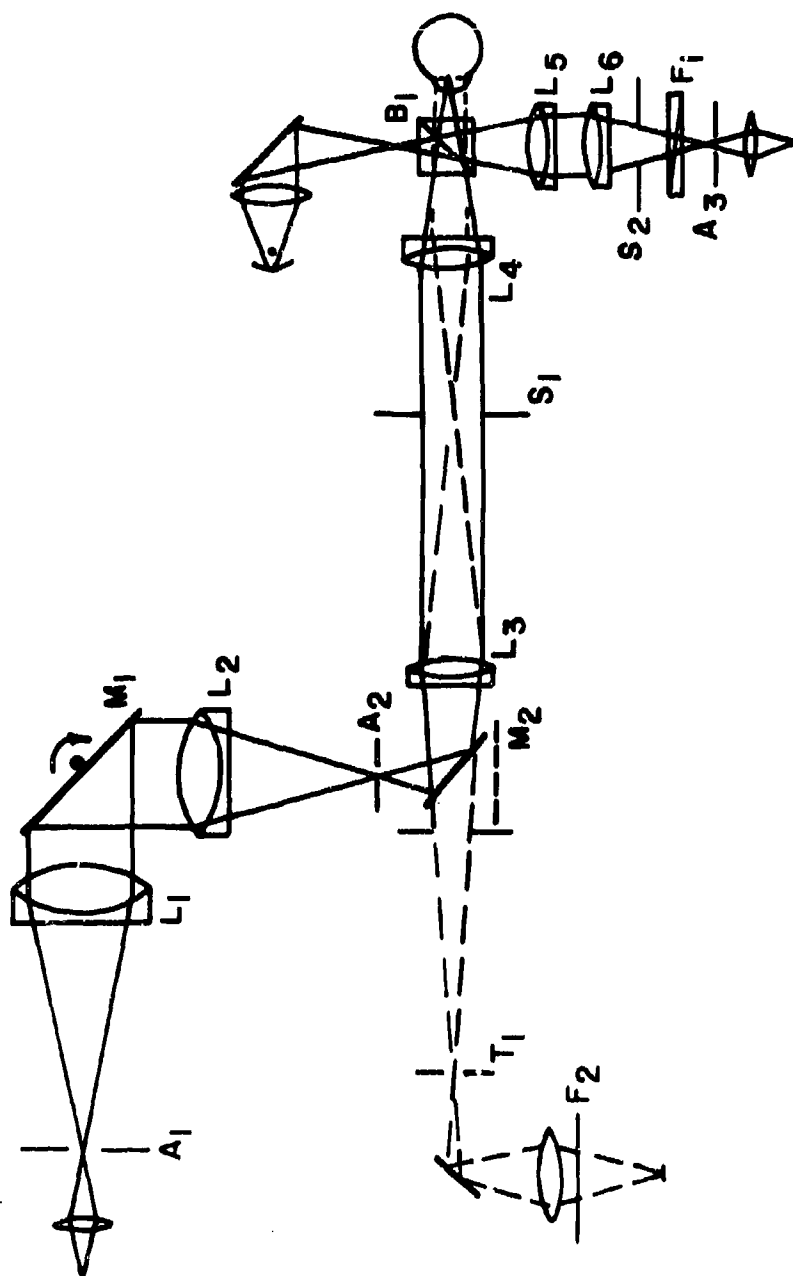
linear with the fraction of unregenerated pigment. From the simple relationship of the after image brightness and the threshold, one might expect to be able to relate the brightness of the after image in the same manner. Figure 12 shows the actual relationship. The ordinates are the log of the retinal illuminance from the measured luminance of the matching field and the abscissa are the instantaneous values of the amount of unregenerated pigment calculated from Rushton's equation for the rate of regeneration of foveal pigments. There seems to be a linear relationship between the log of the background and the fraction of unregenerated pigment for the lower portion of the curve. The form of the curve indicates either that there are two active processes at work causing two limbs of different rate or that the relationship is a power function.

The data are replotted on a log log basis in Figure 13 and reveal a power law relationship between the after image brightness or the log of the incremental threshold and the time following the flash. Figure 14 further verifies the power relationship for two flash energies differing by a fraction of 20. The data points are the group means for six subjects. The slopes for the two types of flashes are identical and very close to an exponent of 3 for the power relationship. Figure 15 shows the results of the brightness matches for two subjects followed over a seven minute period. The individual differences are interesting, and as yet no explanation for them has been found. Both subjects show the same slope in the log log plot of the data, but the early portion of the two recovery curves is shifted by a considerable amount for one observer relative to the other. The latter portion of the recovery history for the subjects coincide.

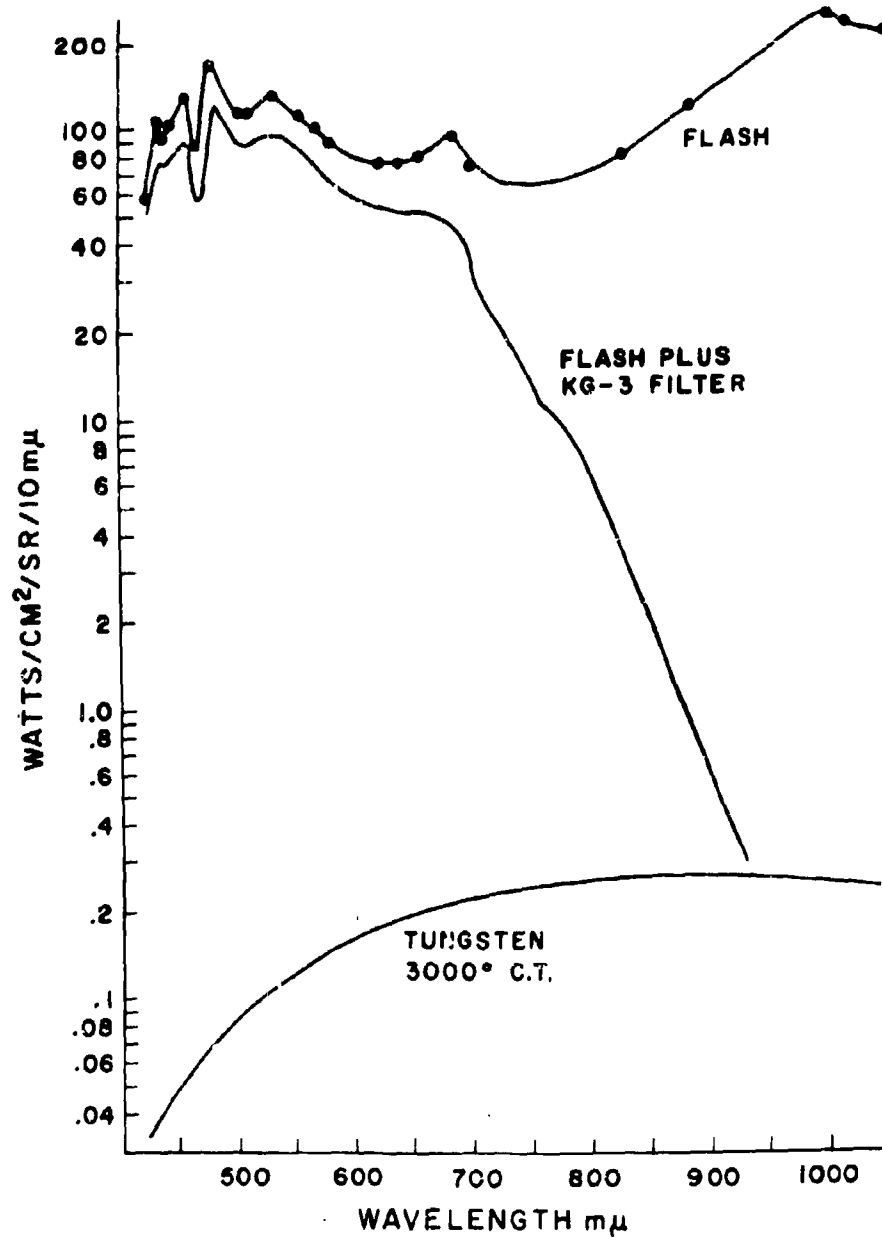
To summarize our work to date, we may point out that we have found a simple relationship between the equivalent background luminance for any given target configuration and the recovery for that target in terms of the instantaneous brightness of the after image. We have also been able to find a simple relationship expressing the rate of fading of the brightness of the after image as a function of time following flashes. Much work remains to be done, however, before we can state the initial brightness of the after image for any given energy of flash or any rate of delivery of that flash energy. Hill and Chisum found a reciprocity failure between intensity and time for short duration, high intensity flashes. Work in our own laboratory has shown this effect to be a marked one and we have examined it over the range from 500 μ sec to 5.0 msec flash durations. It is important to extend the range of flash durations to further investigate the effect of rate of delivery of flash energy on the brightness of the subsequent after image. There is still a considerable amount of work also in the area of recovery times for flashes received in the peripheral part of the retina and for flashes smaller than the recovery targets. It is to be hoped that, within a reasonable period of time, intensive work can be devoted to uncovering simple relationships between initial after image brightness and rate of delivery of flash energy and work can be successfully completed on a predictive model for flash blindness effects.

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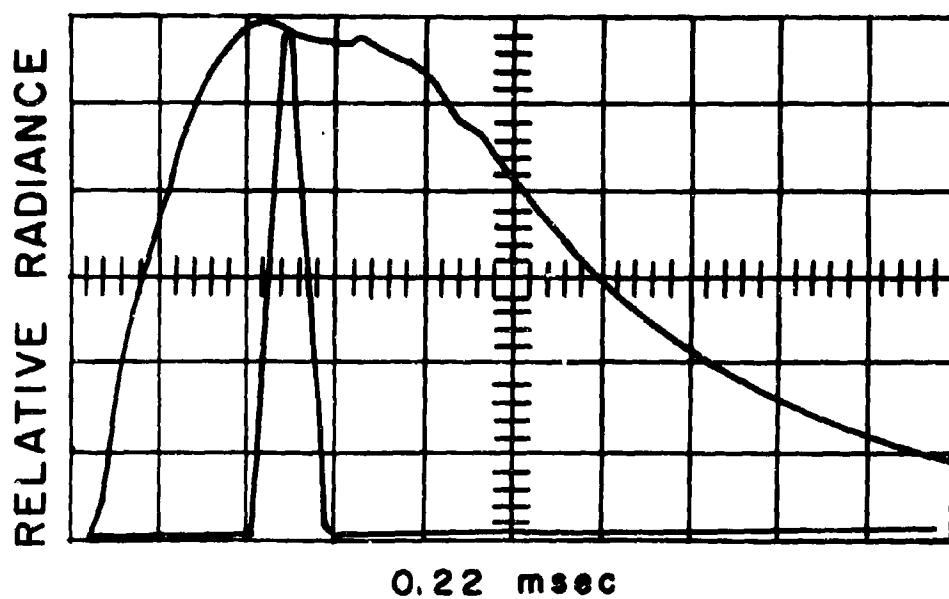
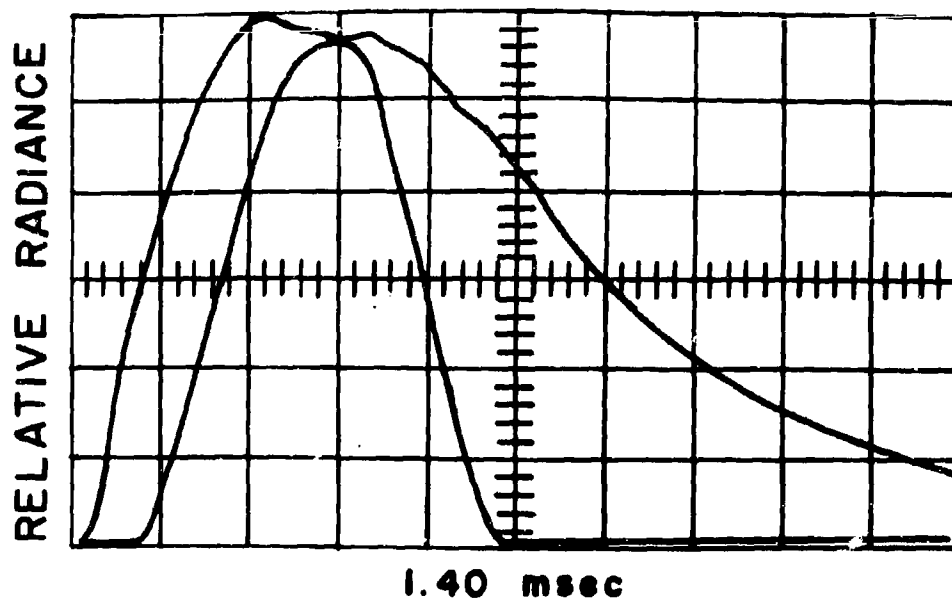
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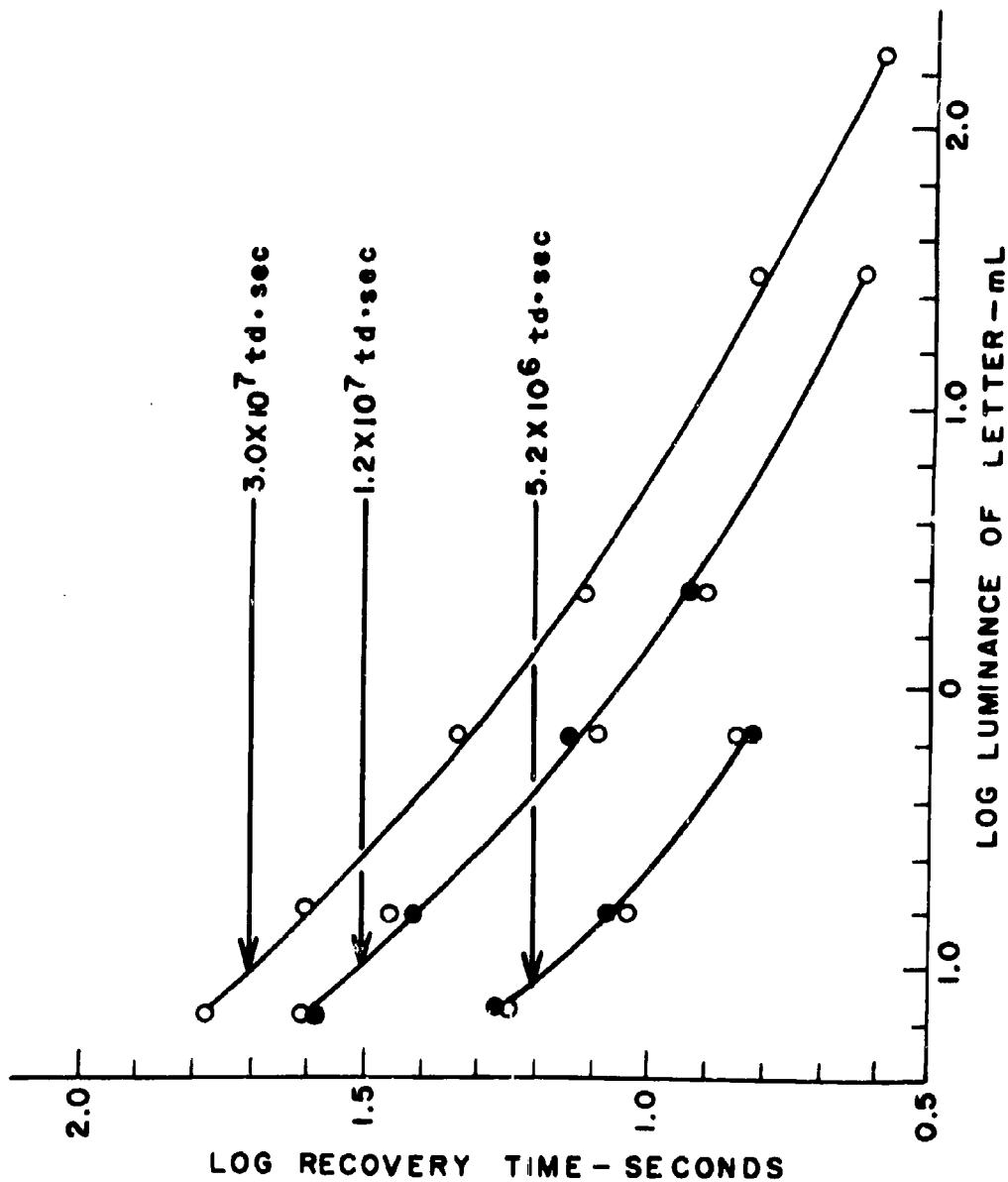
1. Schematic diagram of the flash blindness apparatus.



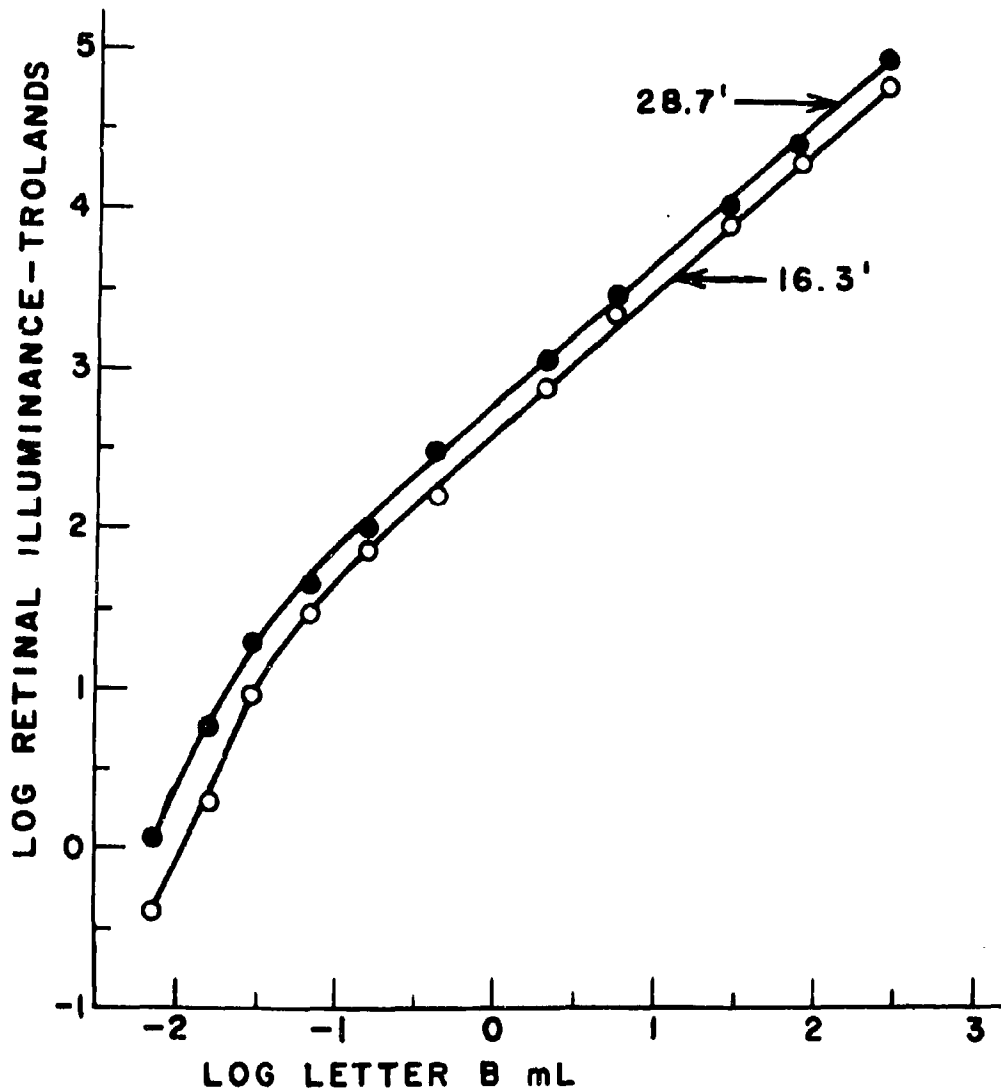
2. Spectral steradiance of the xenon flash source compared with that of tungsten ribbon filament at 3000° color temperature.



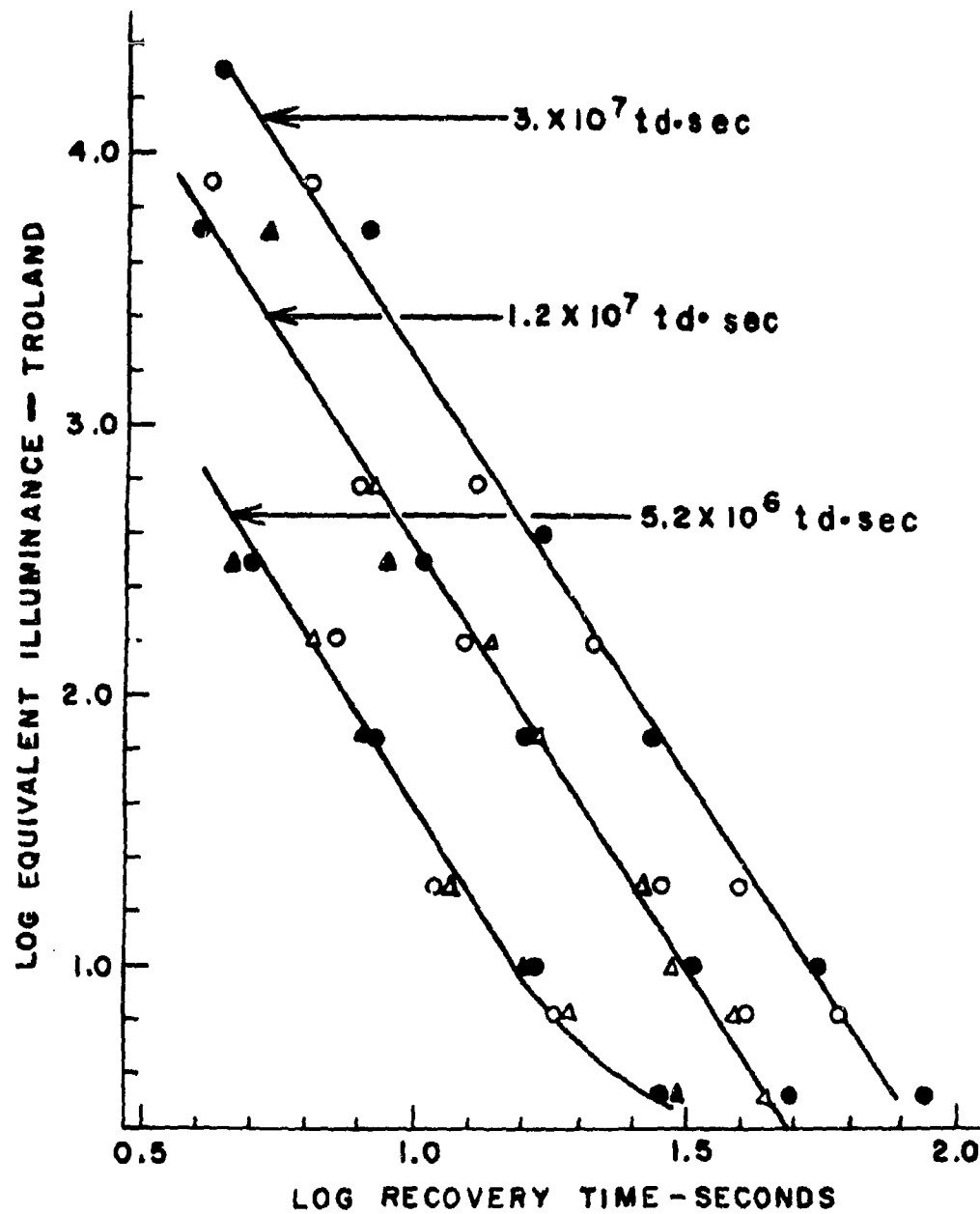
3. Time course of the radiance of the xenon discharge tube.



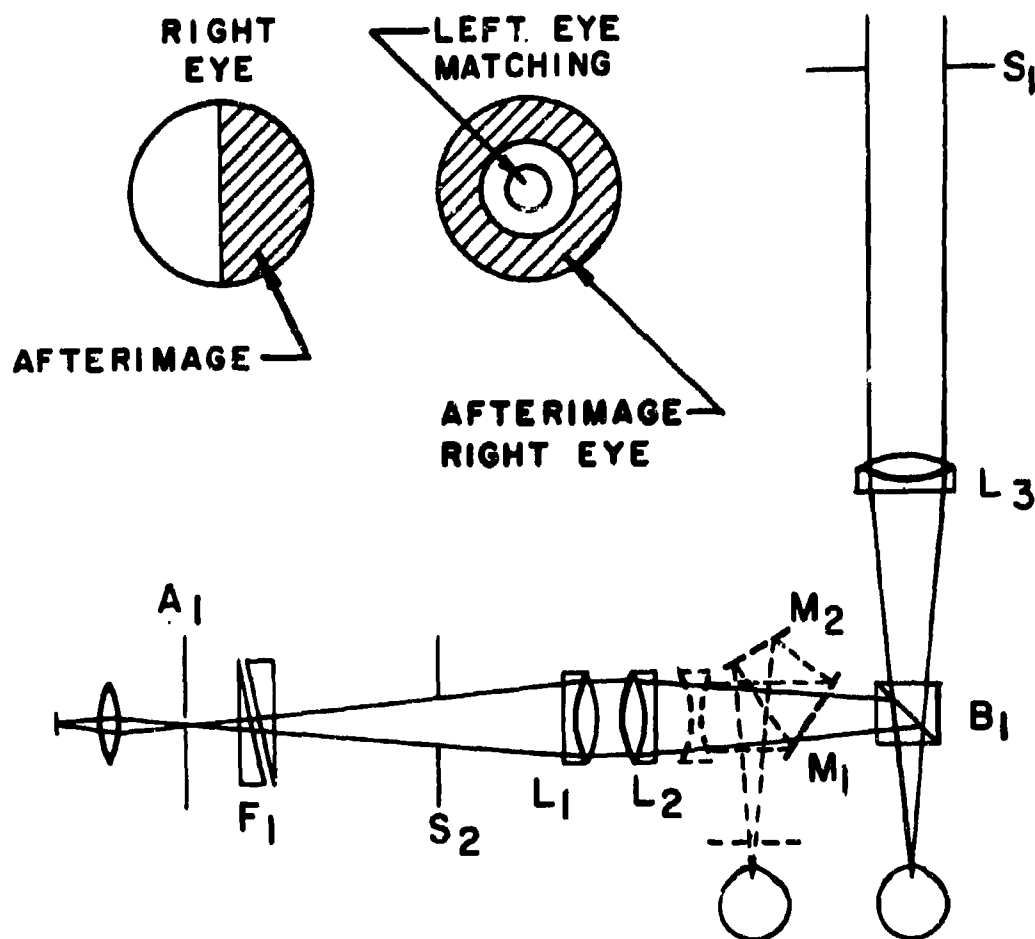
4. The log of the recovery times for 28.7' Sloan-Snellen letters as a function of the log luminance of the letters for three different flash energies.



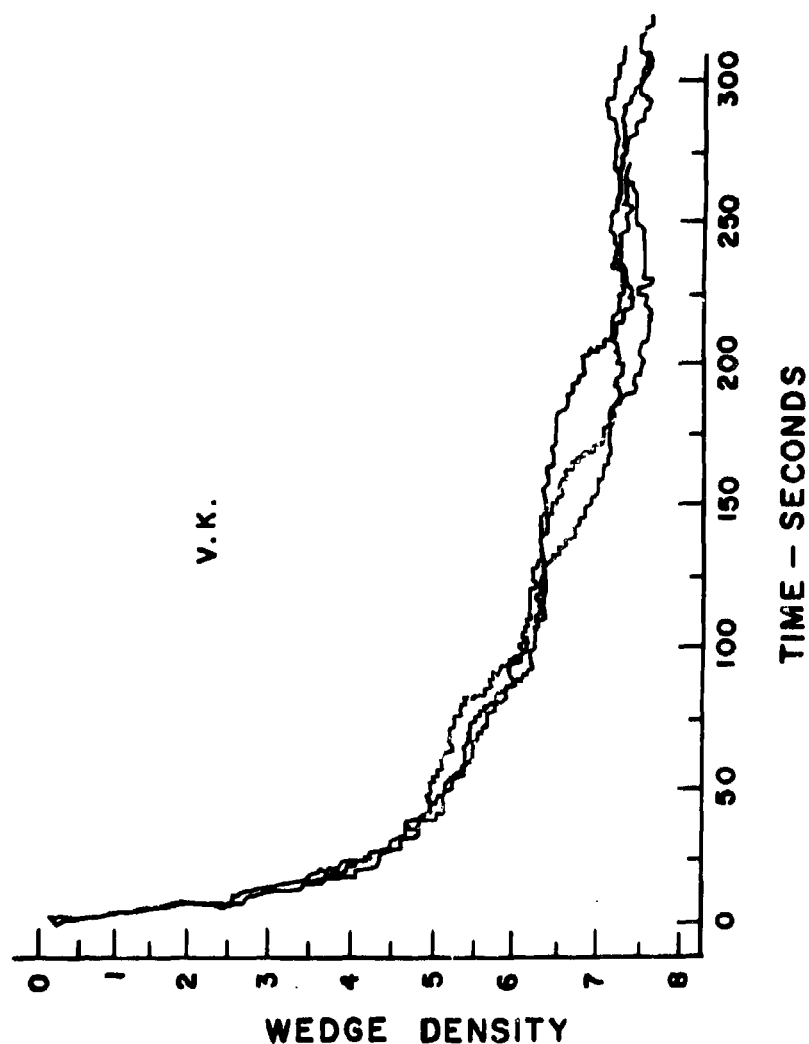
5. The relationship between the log of the retinal illuminance produced by an external field adjusted for threshold detection of the recovery targets as a function of the log of the target luminance.



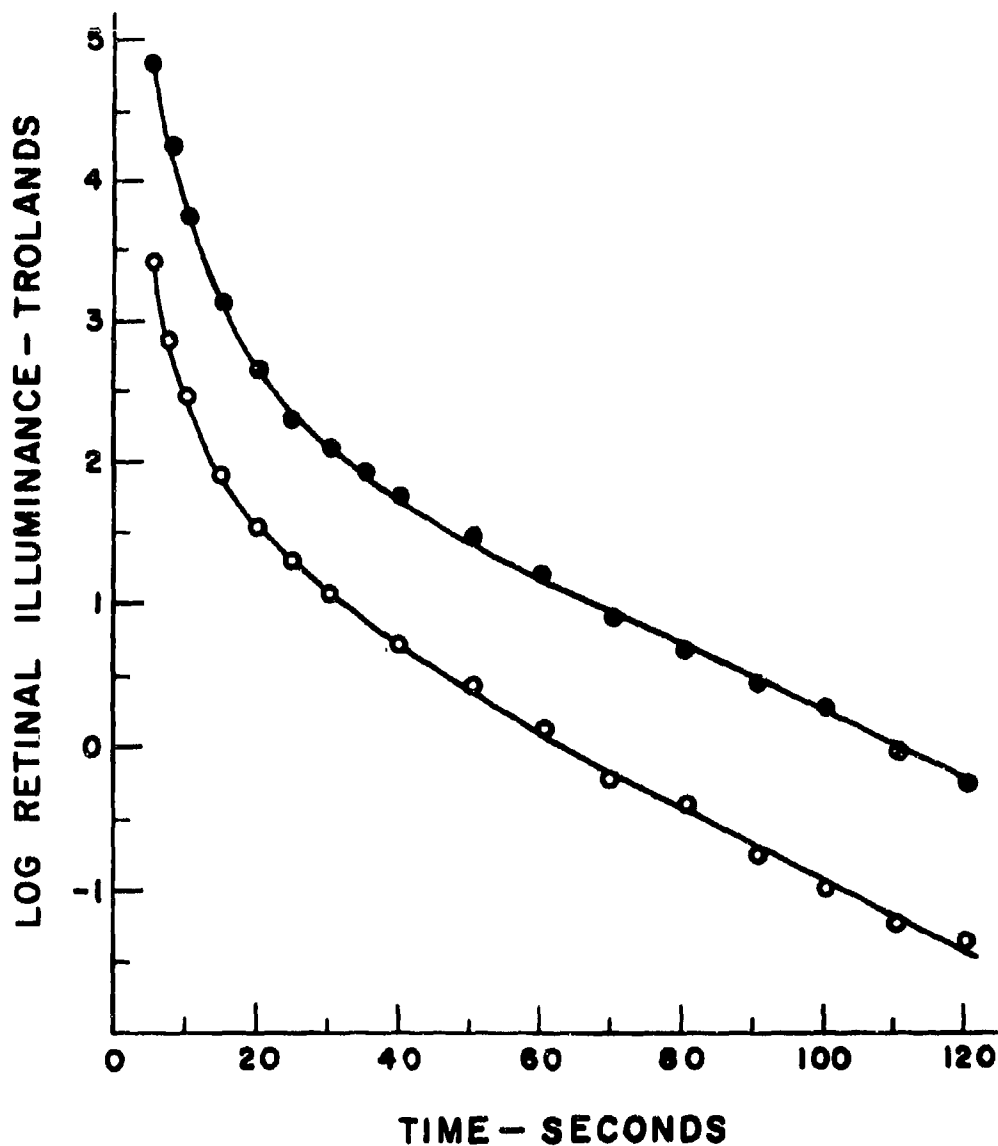
6. Recovery time data plotted on the basis of the log equivalent background illuminance.



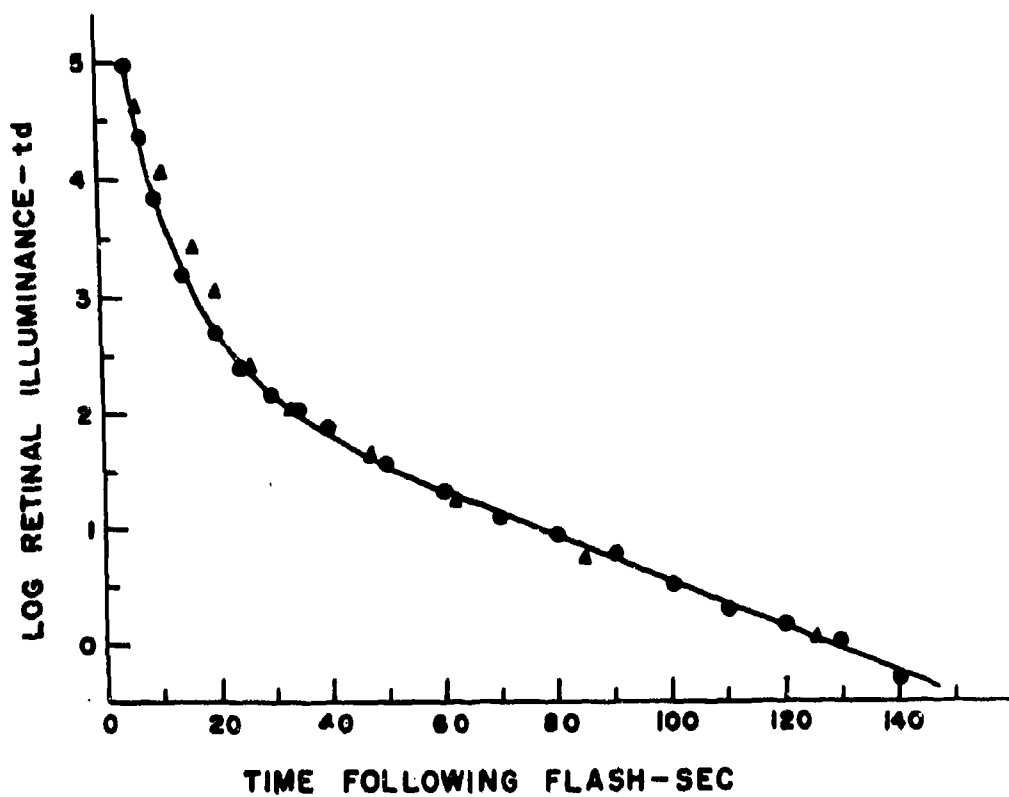
7. Schematic diagram of the modification of the flash blindness apparatus for after image brightness matching experiments.



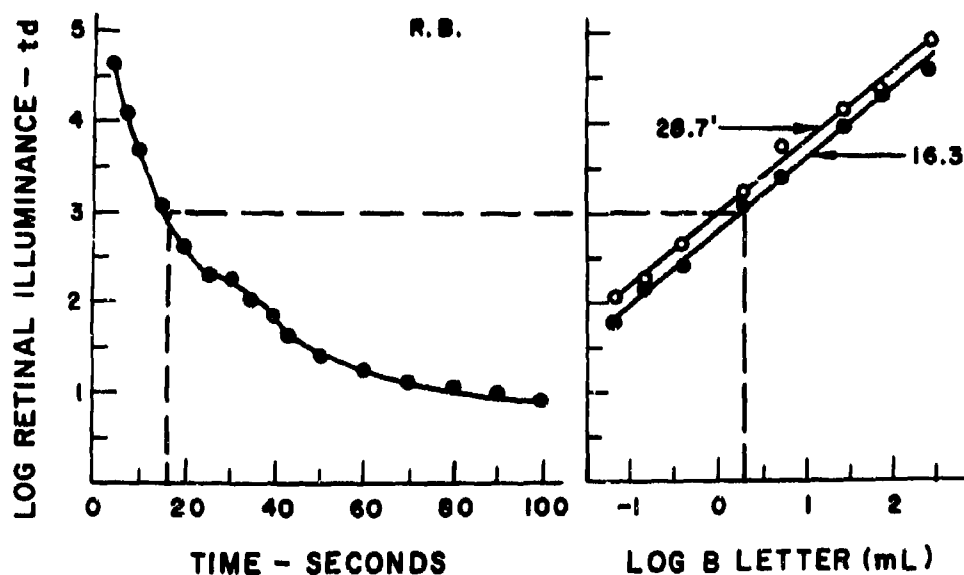
8. The traces of the wedge density required to maintain a brightness match between an external field and the after image as a function of the time following the production of the after image. The three traces were the result of three after image brightness matching experiments by one subject following equal energy flashes of 3×10^7 td·sec.



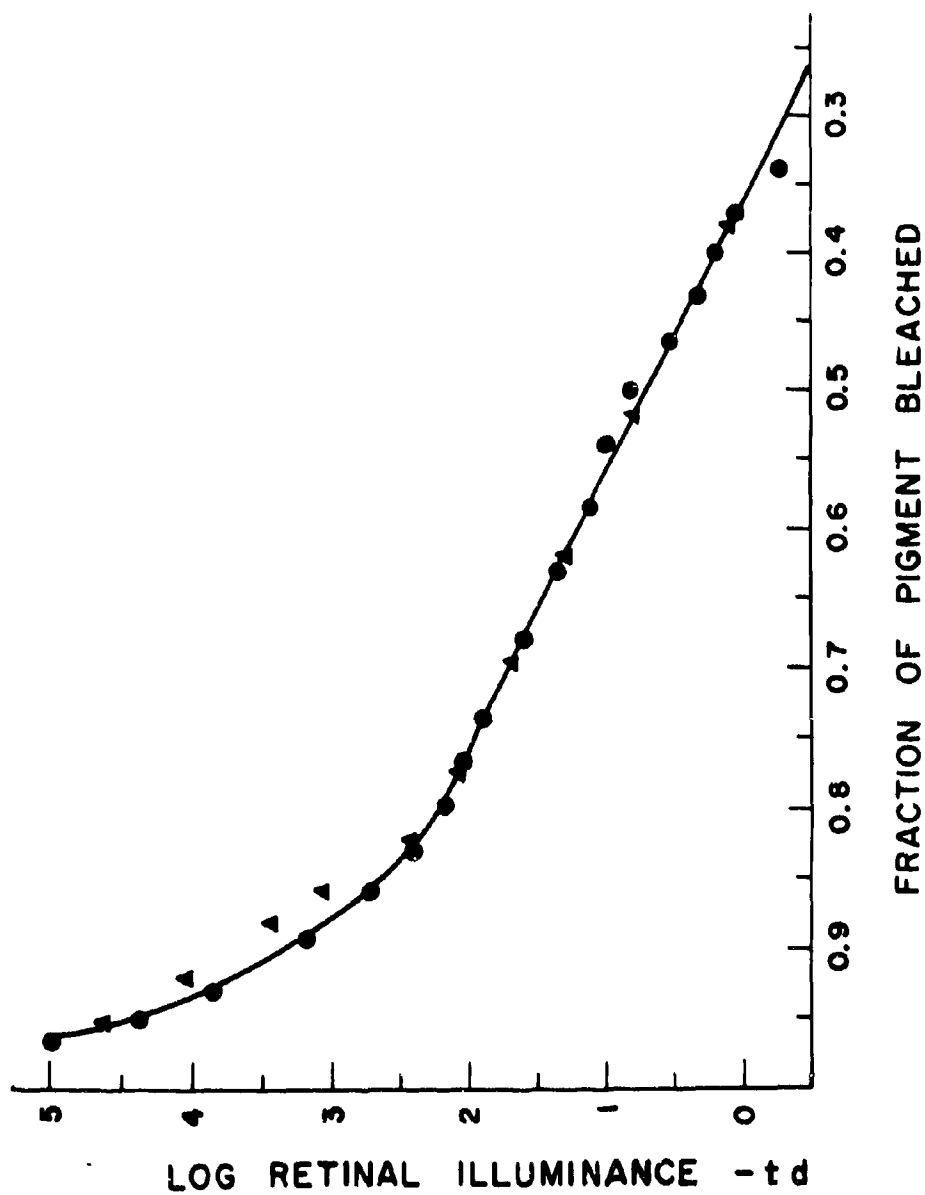
9. The log-retinal illuminance from an external matching field required to maintain a match with the fading after image following flashes of two different energy levels. The data points are the average for six subjects.



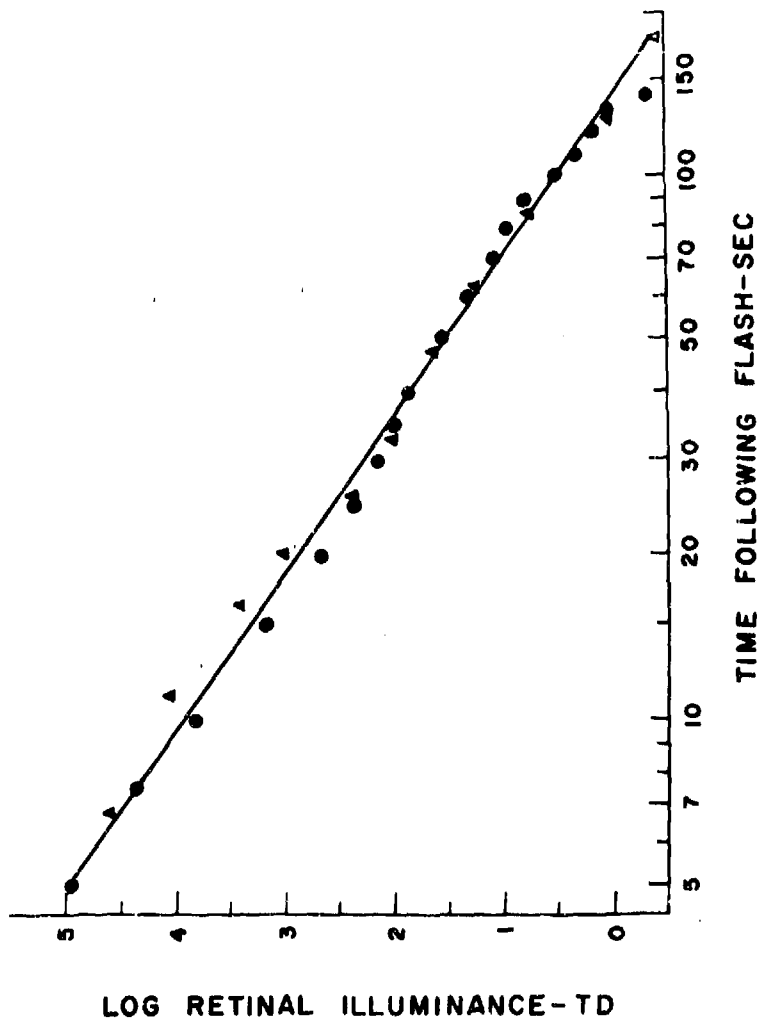
10. The log-retinal illuminance from an external matching field required to maintain a brightness match with the fading after image following flashes of $10^3 \times 10^7$ td·sec. The solid dots are the mean data from the after image brightness matching for six subjects. The triangles are the results from the recovery time experiment for the same six subjects.



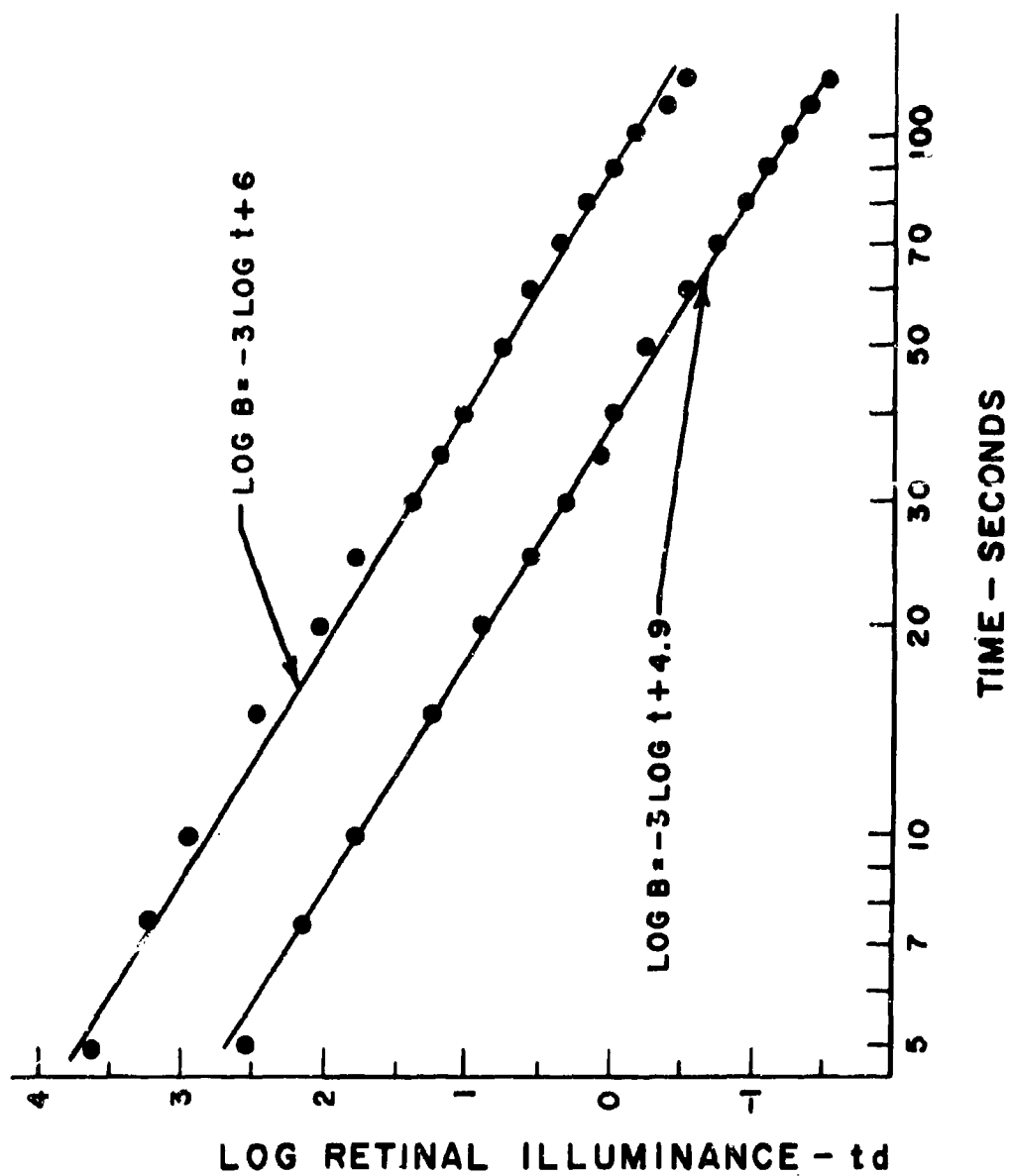
11. Graphical representation of the procedure for predicting recovery time following 3×10^7 td·sec flashes for the 16.3' Sloan-Snellen letter for one subject. The figure on the left shows the results of the after image brightness matching experiment for subject R.B., and the figure on the right shows the results of the equivalent background luminance determination for the two recovery targets.



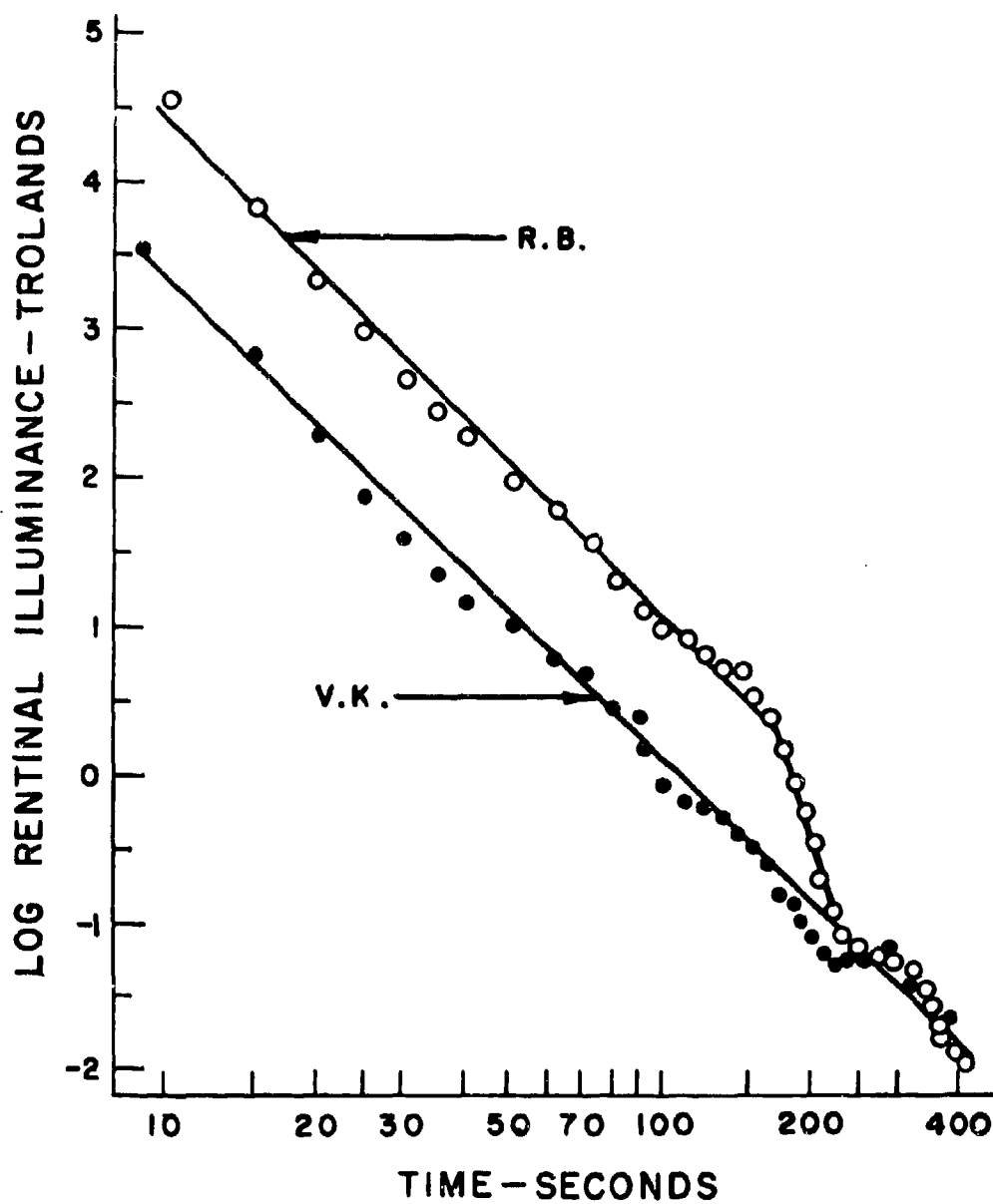
12. The after image brightness data and recovery time data plotted as a function of the fraction of bleached pigment remaining following the flash.



13. The recovery time data and after image brightness data plotted on a log log scale of retinal illuminance and the time following the flash.



14. The power relationship between after image brightness and time following flashes of 3×10^7 td·sec and 2×10^6 td·sec.



15. Log log plots of the retinal illuminance required to match the after image as a function of time following flashes of 3×10^7 td·sec for two different subjects.

FLASH BLINDNESS: INTRAOCULAR EFFECTS

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Presented by Donald I. Fromish

INTRODUCTION

The unanticipated detonation of a nuclear weapon can result in visual exposures which may produce retinal burns, flash blindness or both. The temporal and spatial characteristics of the light which reaches the eyes of an observer are a function of several conditions, among which are weapons size, distance, atmospheric conditions, and duration of the exposure⁹. The visual effects of the light which reaches the eyes are a function of fireball image intensity and size, atmospherically scattered light which enters the eyes, duration of the exposure, preadaptive state of the eyes, retinal geometry of the exposure, entoptic effects of the exposure and interactions among these factors, some of which have been the subject of earlier investigations^{4,10}.

It has been demonstrated that the retinal effect of a stimulus is not perfectly isomorphic with the stimulus^{1,2,3,5,6,7,8,11,12}. An intense stimulus imaged on one part of the retina can reduce the sensitivity of a spatially remote area of the retina. In most cases, investigation of entoptic effects of visual exposures have been concerned with effects produced during exposure to a glare source^{1,2,7,11} but not with effects which persist after removal of the glare source. The entoptic effects which are of concern in the problem of flash blindness are those which persist after removal of the adapting source. In addition, studies have shown that the effects of a high-intensity, very short-duration exposure are not simply a function of the integrated luminance of the exposure as is the case with longer exposures⁴. It may be anticipated therefore, that the entoptic effects of such exposures may also differ

from those resulting from longer exposures.

The purpose of the present investigation is to explore the nature and extent of entoptic adapting effects produced by high-intensity, short-duration visual exposures.

Apparatus

A schematic diagram of the apparatus is shown in Figure 1. The adapting flash is provided by a xenon flash lamp, AF. After passing through the collecting lens at L_1 , and the collimating lens at L_2 , the beam is converged by L_3 at the aperture, A_1 . The shutter, S_1 , is closed except when an adapting flash is required. The beam is again collimated by L_4 before passing through the field stop at FS, which controls the area and location of the adapting flash in the visual field. The beam is converged by L_5 and again collimated by L_6 which places an image of the stop at FS_1 in front of the ocular of the system mounted in the wall of a light tight chamber. The beam is converged by the ocular, E, at the eye point, EP, located inside the light tight chamber. To the eye of an observer positioned at EP by a dental wax impression bite board, the last lens of the ocular is seen in Maxwellian view and appears to be filled with light when the maximum area of the visual field, sixty degrees, is used.

The visual display, or target, consists of a grating pattern, G, of parallel opaque lines separated by clear spaces equal in width to the lines. The grating is mounted in the optical system so that it can be oriented either horizontally or vertically in the view of the observer. Resolution of the grating pattern requires a visual acuity of 0.33. The grating is transilluminated by light from the

tungsten lamp T_1 . From T_1 the beam passes through the collecting lens, L_7 , neutral density filters at F_1 , the collimating lens, L_8 , neutral density filters at F_2 , and is converged at the aperture A_2 by L_9 . The shutter at S_2 controls the duration of the presentation of the visual display. The beam is again collimated by L_{10} before passing through the grating, G . The grating is located at a distance from L_{11} such that the grating image is seen by the observer at a viewing distance of 22.5 inches. The area subtended by the visual display is one degree and is controlled by a field stop, FS_2 , placed in front of the grating. The beam then passes through L_{11} and L_{12} which are identical to L_5 and L_6 . The region of the retina stimulated is controlled by the use of a red fixation point, FP , a small clear cross on an opaque screen, transilluminated by light from a tungsten filament lamp, T_2 . The chromatic composition of the light is controlled by an interference filter at F_3 which is placed in a collimated portion of the beam between L_{14} and L_{15} . The optical character of the fixation point beam is identical with the other two beams of the system. The fixation point is placed at a distance from L_{17} such that the image is seen by the observer as a small red cross at a viewing distance of 22.5 inches and requires an accommodation of 1.75 diopters. The fixation point is positioned so that it appears at the left hand edge of the visual display. The visual display therefore stimulates a foveal area one degree in diameter, centered 30 minutes nasal to the center of the fovea along the horizontal meridian. The pellicle beam splitters, P_1 and P_2 , and the mirror, M , combine the beams entering the ocular so that the observer sees one visual field consisting of a fixation point, a visual display and an adapting flash at the proper intervals, and in the proper

spatial relationship. The area of the adapting flash and the retinal location of the flash are varied by the size and horizontal position of the field stop FS_1 .

The stimulus sequencing, grating orientation, luminance variation and data recording are accomplished by electromechanical devices controlled automatically by a programmed digital logic system. The electromechanical and electronic system is shown schematically in Figure 2. The controls available to the observer are a foot switch, FS, which initiates a trial sequence by way of the logic system, and two response buttons, HS, by which the detection and orientation of a target are indicated.

The electromechanical controls which effect stimulus changes are shown in the electromechanical control section of the figure. The solenoids marked F_1 and F_2 operate filter wheels which control stimulus intensities. The solenoids marked S_2 and S_3 operate shutters which control the grating and fixation point presentation. The step motor, SM, controls the grating orientation. The timer, C, provides a measure of the observer's response time. Sequencing of the operation of the devices, and the inputs to the printer from the observer controls, the electromechanical controls and the response timer are mediated by the digital logic complex. In this experiment, the printer inputs are filter wheel positions, which determine test stimulus intensities, grating orientation, response correctness, trial number and response time.

Calibration

The luminances of the adapting and display fields were calculated from the spectral irradiances measured with an EG&G Model

580/585 spectroradiometer. The spectroradiometer was positioned in front of the ocular of the system and the irradiance measured at 10 millimicron intervals between 390 and 750 millimicrons. The illuminance at the spectroradiometer was calculated using the ICI Standard Observer luminosity data. The luminance of the last lens of the optical system was then calculated from the illuminance at the spectroradiometer surface. On the basis of this procedure, the maximum luminance of the display field was found to be 4.124 log millilamberts. The peak luminance of the adapting field was found to be 7.59 log millilamberts. A 1P39 phototube was used to obtain an oscilloscope tracing of the light output of the xenon flash lamp. The tracing obtained is shown in Figure 3. The decay rate of the light output is approximately exponential; therefore, in order to obtain an estimate of the duration of an equivalent square wave, the duration was measured at one-third peak amplitude. The duration at one-third peak amplitude is 150 microseconds. The integrated luminance of the adapting field is 3.77 log millilambert-seconds.

Throughout the course of the experiment, the adapting flashes were monitored with a photocell mounted behind the pellicle beam splitter, P₁ (Figure 1). The responses following any flash which deviated more than two percent from that shown in Figure 3 were discarded.

The neutral density filters used in the display field were ganged inconel and gelatin filters. Since the density of ganged filters is different from the sum of the densities of each filter, the transmissions ($\frac{1}{\text{density}}$) of the filter groups were measured with a Mabeth illuminometer. The densities of the filter groups are shown in Table 1.

The spatial calibrations were made with a depth calibrated line-of-sight telescope mounted so that it could be pivoted around the focal point of the system. The angular measurements were read to 15 seconds from a micrometer scale mounted on the pivot. The depth measurements were read in inches from a scale on the focusing dial of the telescope.

Procedure

The adapting flash sizes and retinal locations relative to the test display are shown in Table 2. The test display was always viewed in foveal vision and subtended a visual angle of one degree. For each of the eight adapting flash areas used, the condition A retinal location was such that the test display was centered in the area stimulated by the adapting flash. The remaining four conditions apply for all adapting flash areas except the 60 degree flash area, the maximum area which could be presented through the optical system. In the B condition, the adapting flash was presented so that the edge of the display was tangent to the area stimulated by the adapting flash. In the C, D and E conditions the adapting flash position was shifted so that the separation between the display and the area stimulated by the adapting flash was increased by one-half degree over the preceding condition. The descriptions in Table 2 are given in terms of retinal separation between the centers of the display and the adapting flash. The same display luminances were investigated for all adapting flash conditions. The luminances were: -0.40, -0.17, -0.10, -0.01, 0.33, 0.42 and 0.92 log millilamberts.

For each experimental session one or two of the thirty-seven control or experimental conditions were used. At the start of a

session the observer, O, was seated in the light tight chamber and permitted to dark adapt for twenty minutes. At the end of the dark adaptation period, a buzzer was sounded and the fixation cross was turned on. The O positioned himself on the dental impression bite board and fixated the cross. When he was properly positioned and accommodated so that he could see the fixation cross clearly, he depressed the foot switch which exposed the adapting flash. The impulse of a photoreceiver which detected the flash activated a logic channel and opened the display beam. As soon as the O was able to determine the orientation of the display grating he pressed one of his two response buttons on the hand switch. Immediately after a response, the display beam was closed momentarily while the filters were changed, and the grating orientation was adjusted according to a predetermined schedule. The beam was opened again and the next display was presented. This sequence occurred five times following each adapting flash, and continued for each condition until nine adapting flashes had been presented. Following each presentation of a display, the trial number, filter wheel positions, grating orientation, response correctness and response time were printed. Following every fifth response, the shutters in all beams were closed and all of the O's controls were deactivated. The buzzer was sounded after a specified time interval to signal the O to begin the next sequence. There were at least three minutes between successive presentations of the adapting flash and at least ninety seconds between the last test display and the next adapting flash. Most experimental sessions lasted approximately two hours including the twenty-minute dark adaptation period. However, if an observer

became fatigued or uncomfortable in any way, the session was terminated. Complete data were obtained for four observers.

Results

The median response times are presented in Tables 3 through 6 for each observer over all experimental conditions. The response times are measured from the one-half peak amplitude point of the leading edge of the adapting flash.

The data for each display luminance are presented graphically in Figure 4 to show response times as a function of adapting flash area. The display was centered in the area stimulated by the adapting flash. These show that as the visual angle subtended by the adapting flash is increased in size from one-half degree to two degrees, the response time increases. It is also evident in Figure 4 that response time decreases when the area subtended by the adapting flash is increased from ten degrees to sixty degrees. The data for the lowest display luminance are more irregular than for the higher display luminances.

The data for three display luminances are presented graphically in Figure 5 to show response time as a function of the separation between the centers of the display and adapting fields. The data for all observers show greatest differences in response times between the overlap and immediately adjacent conditions. Each curve in the figure represents the response times for a different adapting flash area. The differences between the first two points in each curve, the overlapping condition and the immediately adjacent condition, increase as the area of the adapting flash increases.

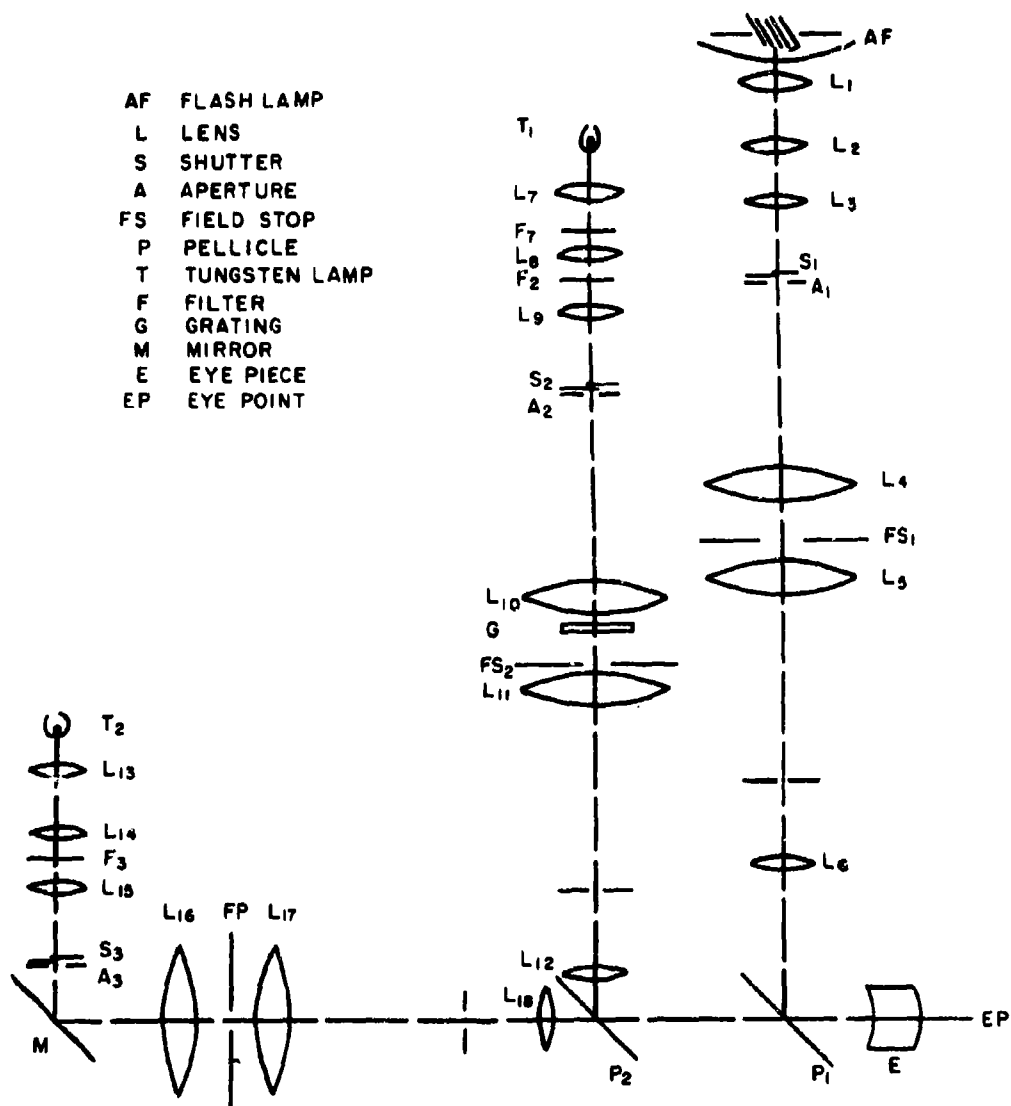
The data for the condition in which the display field was

presented immediately adjacent to the area stimulated by the adapting flash are presented graphically in Figure 6 to show response time as a function of adapting flash area for each display luminance. The only flash display center separation which occurred for more than two adapting flash areas was the two and one-half degree separation. Response times as a function of adapting flash area for the two and one-half degree separation between the adapting flash and display areas are shown in Figure 7. In both the adjacent (Figure 6) and two and one-half degree center separation conditions, (Figure 7) there appears to be a consistent increase in response time when the adapting flash area is increased from one to two degrees, but no consistent size effect for adapting flash areas greater than two degrees.

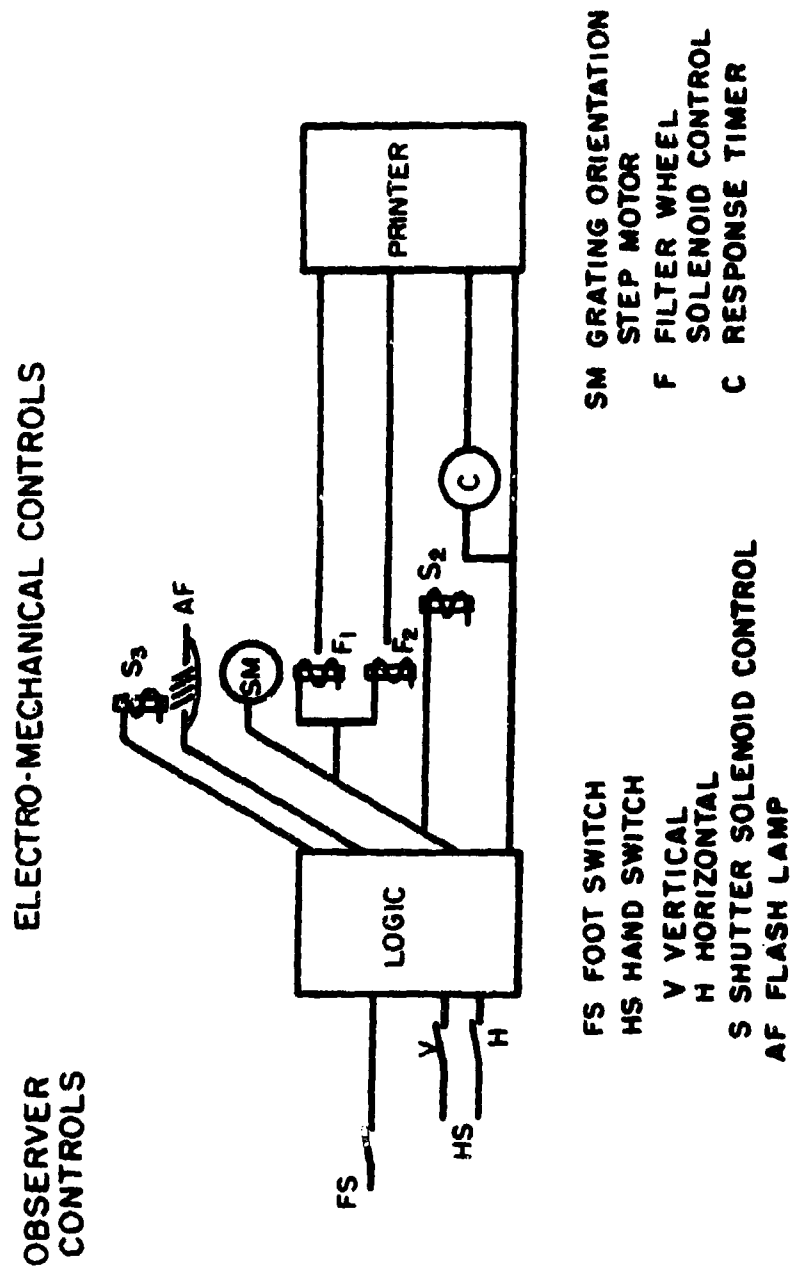
In order to generalize from the data obtained in the present experiment to flashes of other intensities and durations, the sixty degree flash data were compared with the nominally full-field data from an earlier experiment in which similar flash duration and integrated luminance and display conditions prevailed⁴. Table 7 shows the comparative data. Data were obtained for only one of the observers in both studies. The overall medians for the observers in the two studies are very similar. In order to estimate response times for exposures of higher intensities than were used in the present study, but with similar areal conditions, the relationships found here can be assumed to hold. The search for a source of greater intensity for which the areal control exercised in the present study can be utilized has been intense and is continuing. When such a source is obtained, the assumption regarding the generality of the results of this study will be examined experimentally.

Summary

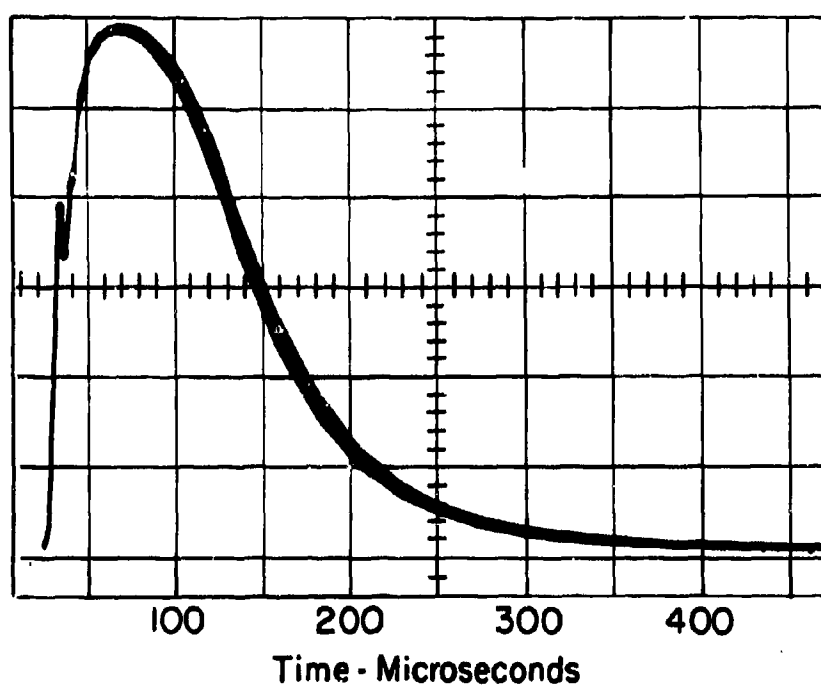
The times required to detect a simple display were measured following exposure to eight high-intensity, short-duration adapting flash areas presented in eighteen retinal locations. Variations in both the adapting flash area and retinal location produced variations in the time required to respond to the display. The response times for the various experimental conditions indicate that intraocular effects operate in flash blindness, with the effect of producing small but consistent increases in foveal response times following extra-foveal stimulation by an adapting flash.



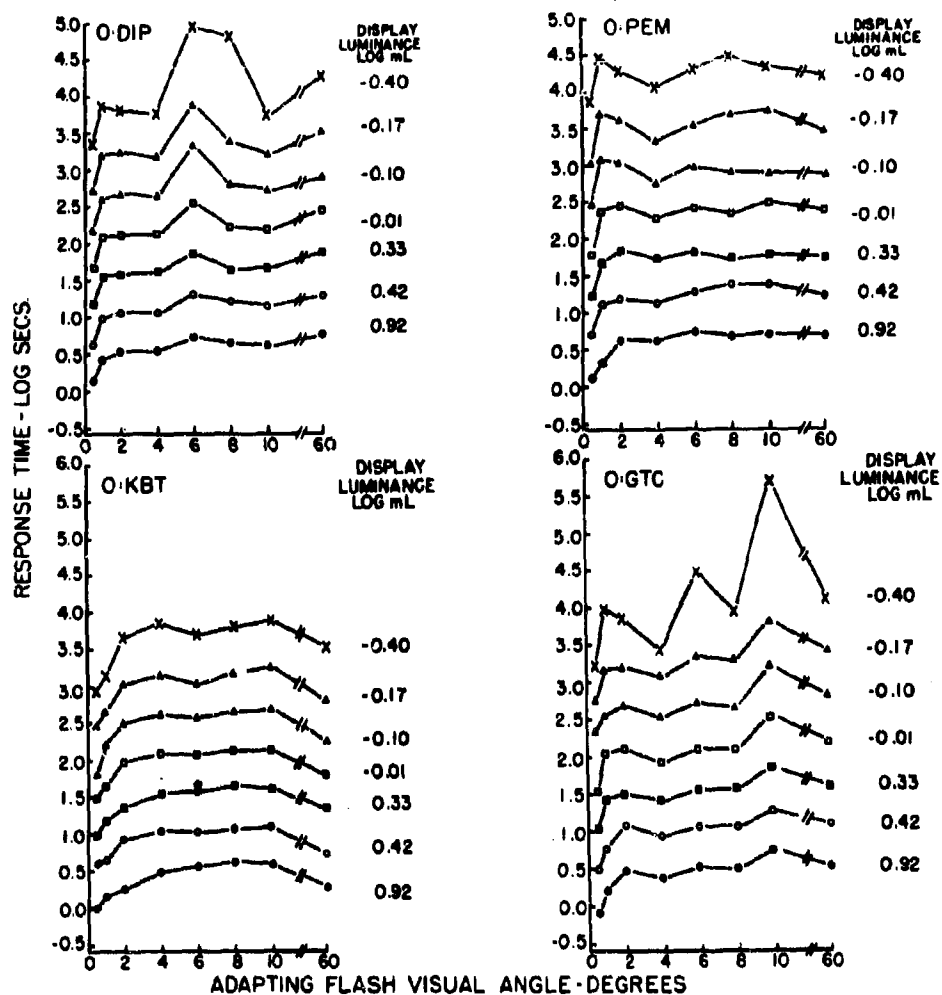
1. Optical system schematic diagram.



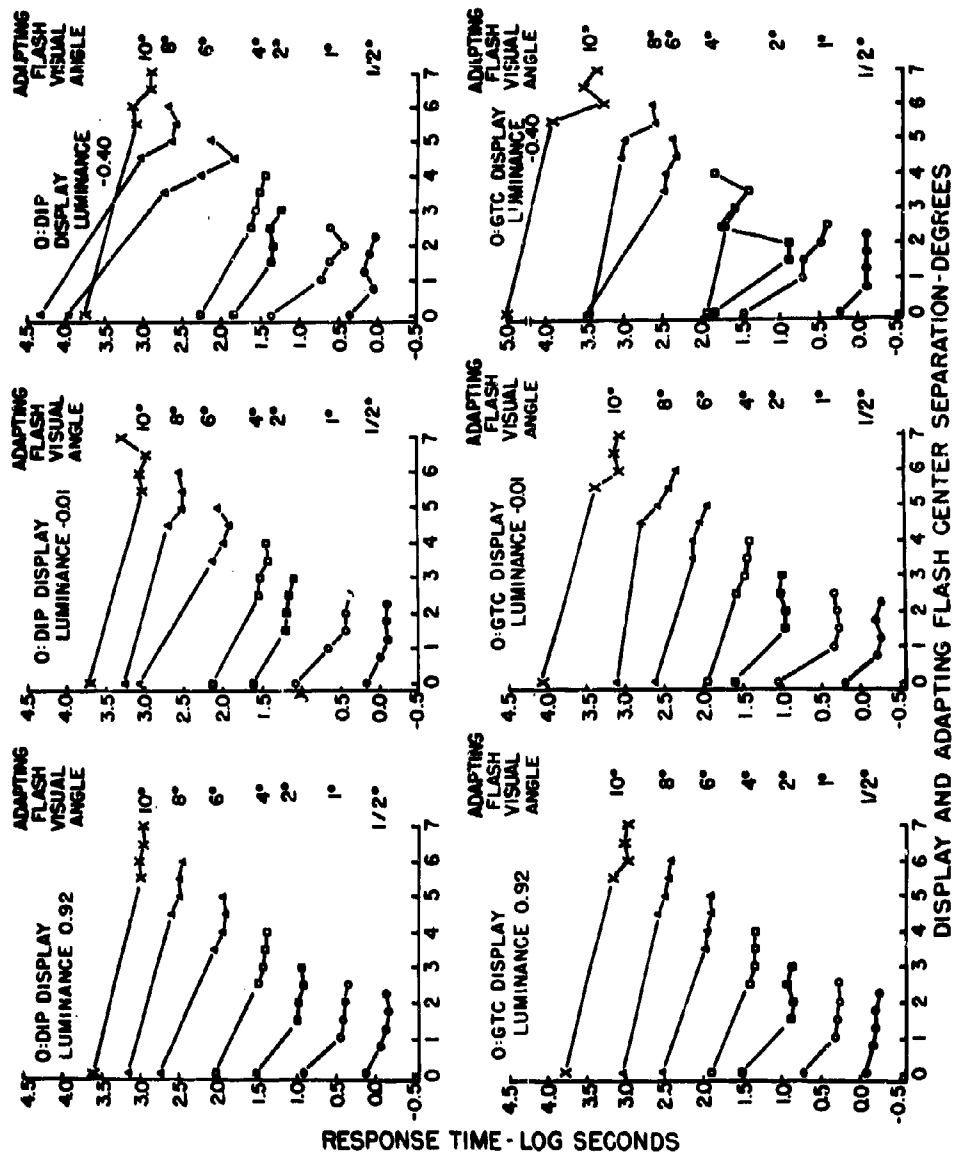
2. Control and data recording system schematic diagram.



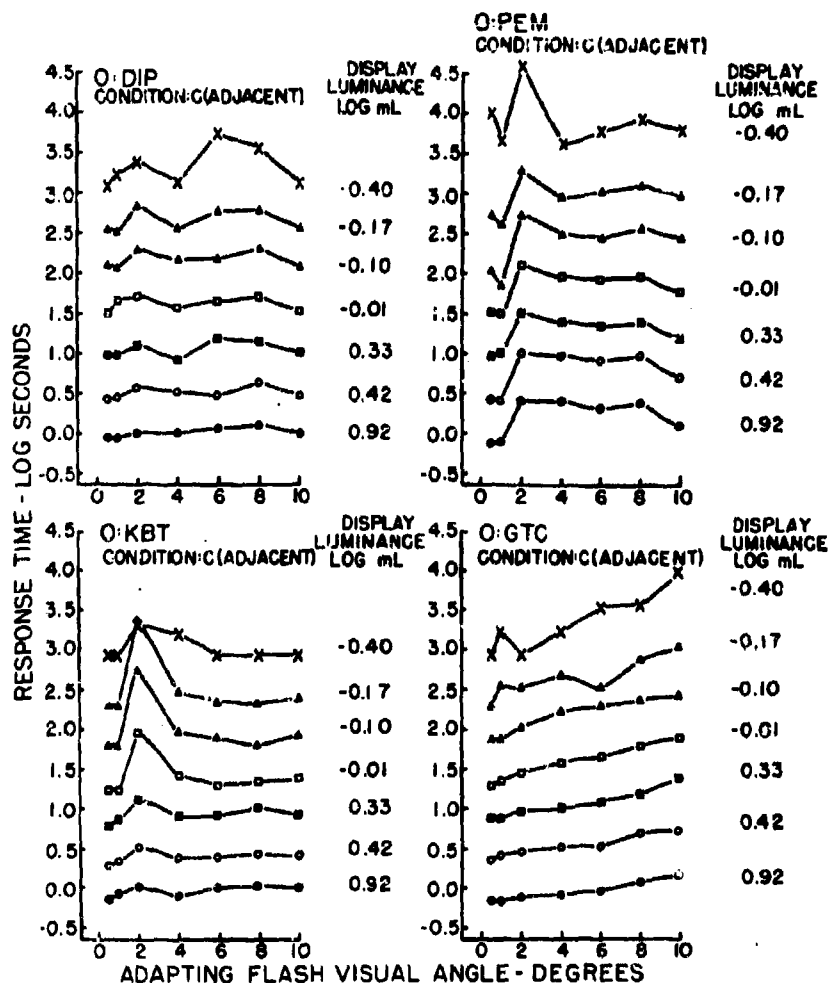
3. Photograph of CRO tracing showing the adapting flash duration.
The duration was measured at one-third peak amplitude.



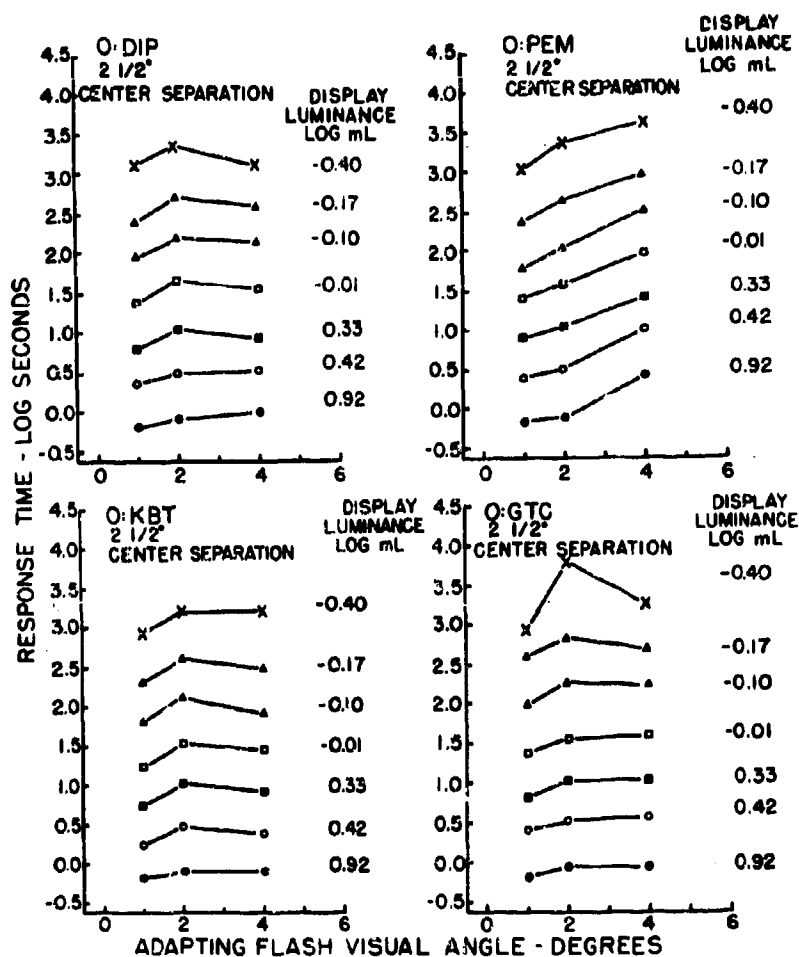
4. Response time as a function of adapting flash visual angle for the condition in which the adapting flash overlapped the display area. All curves above the lowest in each graph have been moved upward successively by 0.5 on the ordinate scale to avoid confusion. The true ordinate value, therefore, may be read by subtracting 0 from the ordinate of the lowest curve, 0.5 from the second, 1 from the third, etc.



5. Response time as a function of the display-adapting flash center separation. All curves above the lowest in each graph have been moved upward successively by 0.5 on the ordinate scale.



6. Response time as a function of adapting flash visual angle for the condition in which the adapting flash and display areas were immediately adjacent. All curves above the lowest in each graph have been moved upward successively by 0.5 on the ordinate scale to avoid confusion. The true ordinate value, therefore, may be read by subtracting 0 from the ordinate of the lowest curve, 0.5 from the second, 1 from the third, etc.



7. Response time as a function of adapting flash visual angle for the condition in which the center of the adapting flash was separated from the center of the display area by 2.5 degrees. All curves above the lowest in each graph have been moved upward successively by 0.5 on the ordinate scale to avoid confusion. The true ordinate value, therefore, may be read by subtracting 0 from the ordinate of the lowest curve, 0.5 from the second, 1 from the third, etc.

Gloria T. Chisum

Table 1. Display filter density and luminance.

Display	Density	Display Luminance (Log mL)
1	3.204	0.92
2	3.704	0.42
3	3.794	0.33
4	4.134	-0.01
5	4.224	-0.10
6	4.294	-0.17
7	4.524	-0.40

Table 2. Experimental design; Separation (degrees of visual angle) between the center of the display and adapting flash.

Experimental Condition	Adapting Flash Visual Angle (Degrees)							
	0.5	1.0	2.0	4.0	6.0	8.0	10.0	60.0
Control	No Flash							
A	0	0	0	0	0	0	0	0
B	0.75	1.0	1.5	2.5	3.5	4.5	5.5	-
C	1.25	1.5	2.0	3.0	4.0	5.0	6.0	-
D	1.75	2.0	2.5	3.5	4.5	5.5	6.5	-
E	2.25	2.5	3.0	4.0	5.0	6.0	7.0	-

Adapting Flash Area (Degrees)	Display - Adapting Flash Center Separation	Display Luminance (Log mL)						
		0.92	0.42	0.33	-0.01	-0.10	-0.17	-0.40
1/2°	0°	0.83	1.03	1.19	1.17	2.24	1.87	1.74
	3/4°	0.71	0.74	0.80	0.66	0.77	0.64	0.85
	1 1/4°	0.66	0.64	0.73	0.59	0.64	0.64	0.85
	1 3/4°	0.68	0.82	0.72	0.69	0.76	0.71	0.85
	2 1/4°	0.60	0.68	0.73	0.57	0.64	0.64	0.85
1°	0°	1.72	1.98	2.77	3.74	3.83	4.88	9.86
	1°	0.71	0.84	0.79	0.74	0.80	1.13	1.78
	1 1/2°	0.66	0.75	0.73	0.64	0.83	0.66	1.71
	2°	0.62	0.75	0.73	0.69	1.11	0.94	1.02
	2 1/2°	0.64	0.80	0.65	0.74	0.96	1.23	0.85
2°	0°	3.22	4.07	3.46	4.24	5.14	5.25	7.43
	1 1/2°	0.80	0.94	0.97	0.95	1.10	1.09	0.87
	2°	0.76	1.01	0.92	0.94	1.03	0.86	0.85
	2 1/2°	0.88	1.04	1.06	1.11	1.83	2.04	5.89
	3°	0.78	1.12	0.91	1.03	2.26	1.69	3.93
4°	0°	2.54	2.95	2.71	2.93	3.54	3.88	2.84
	2 1/2°	0.84	1.17	1.08	1.25	1.72	1.53	1.78
	3°	0.72	0.99	0.91	0.97	1.19	1.25	1.26
	3 1/2°	0.70	0.82	0.81	0.90	1.07	1.14	0.86
	4°	0.71	0.96	0.80	0.84	1.14	0.92	2.46
6°	0°	3.47	3.81	3.89	4.25	5.52	7.60	31.12
	3 1/2°	0.94	1.19	1.26	1.45	2.00	1.05	3.46
	4°	0.91	1.30	1.36	1.43	1.66	2.10	3.21
	4 1/2°	0.81	1.16	0.96	1.17	1.88	1.64	2.44
	5°	0.84	0.84	1.06	0.96	1.28	1.35	2.71
8°	0°	3.37	3.77	3.88	4.12	4.73	6.41	9.10
	4 1/2°	1.22	1.60	1.59	2.05	2.43	2.51	3.73
	5°	0.98	1.08	1.28	1.23	1.63	1.69	3.37
	5 1/2°	0.88	0.97	0.95	0.86	0.96	0.86	1.38
	6°	0.82	0.91	0.81	0.71	0.97	0.71	1.40
10°	0°	5.93	6.05	7.64	11.42	16.68	20.30	105.18
	5 1/2°	1.46	1.70	2.50	2.58	2.82	3.60	9.81
	6°	0.92	1.24	1.18	1.26	1.74	1.64	2.06
	6 1/2°	1.00	1.26	1.20	1.42	1.69	1.80	3.78
	7°	0.94	1.10	1.06	1.24	1.37	1.51	2.47
60°		3.55	4.04	4.26	5.07	6.89	8.46	13.19

Median Response Time (secs.) For Eight Adapting Flash Areas,
Seven Display Luminances and Five Separations Between the Display
and Adapting Flash. Display Visual Acuity Requirement: 0.33

Observer: GTC

Table 3

Adapting Flash Area (Degrees)	Display - Adapting Flash Center Separation	Display Luminance (Log mL)						
		0.92	0.42	0.33	-0.01	-0.10	-0.17	-0.40
1/2°	0°	1.36	1.31	1.58	1.50	1.53	1.67	2.27
	3/4°	0.87	0.86	0.94	0.99	1.29	1.13	1.19
	1 1/4°	0.73	0.73	0.77	0.80	0.99	0.94	1.50
	1 3/4°	0.68	0.68	0.91	0.83	0.93	0.93	1.31
	2 1/4°	0.72	0.74	0.74	0.81	1.01	0.88	1.10
1°	0°	2.63	3.05	3.49	3.98	4.01	4.95	7.35
	1°	0.88	0.89	0.96	1.48	1.17	1.02	1.65
	1 1/2°	0.81	0.73	0.82	0.88	0.98	0.98	1.35
	2°	0.77	0.74	0.93	0.88	0.96	0.82	0.88
	2 1/2°	0.68	0.73	0.65	0.78	0.92	0.82	1.36
2°	0°	3.42	3.68	3.81	4.26	4.83	5.43	6.84
	1 1/2°	1.01	1.20	1.28	1.62	1.91	2.22	2.31
	2°	0.98	1.07	1.15	1.54	2.06	2.05	2.20
	2 1/2°	0.84	0.98	1.13	1.47	1.59	1.68	2.34
	3°	0.88	0.89	1.00	1.23	1.21	1.54	1.76
4°	0°	3.54	3.63	4.19	4.33	4.56	4.75	5.93
	2 1/2°	1.01	1.05	0.87	1.15	1.41	1.24	1.34
	3°	0.88	0.83	0.96	1.10	1.17	1.08	1.23
	3 1/2°	0.80	0.69	0.86	0.85	0.83	0.88	1.07
	4°	0.77	0.79	0.82	0.92	1.16	0.87	0.89
6°	0°	5.48	6.49	7.60	11.67	25.22	24.73	89.41
	3 1/2°	1.16	0.95	1.56	1.40	1.49	1.81	5.25
	4°	0.91	0.89	0.93	0.98	1.25	1.09	1.86
	4 1/2°	0.80	0.79	0.74	0.82	1.02	0.78	0.69
	5°	0.89	1.14	0.99	1.18	1.63	1.38	1.41
8°	0°	4.54	5.25	4.52	5.47	6.45	7.85	65.81
	4 1/2°	1.28	1.38	1.40	1.60	2.00	1.86	3.47
	5°	0.97	0.93	0.97	1.07	1.42	1.23	1.42
	5 1/2°	0.98	0.84	1.00	1.01	1.17	1.02	1.26
	6°	0.91	1.07	0.95	1.13	1.34	1.23	1.59
10°	0°	4.15	4.45	4.68	4.91	5.30	5.31	5.59
	5 1/2°	1.00	0.91	1.04	1.04	1.17	1.10	1.27
	6°	1.08	1.08	1.17	1.20	1.33	1.23	1.45
	6 1/2°	0.96	0.87	0.83	0.91	1.08	0.82	0.84
	7°	0.94	0.92	0.82	1.96	1.22	0.94	0.81
60°		5.81	6.15	7.75	9.36	7.94	10.74	18.53

Median Response Time (secs.) For Eight Adapting Flash Areas, Seven Display Luminances and Five Separations Between the Display and Adapting Flash. Display Visual Acuity Requirement: 0.33

Observer: DIP

Table 4

Adapting Flash Area (Degrees)	Display - Adapting Flash Center Separation	Display Luminance (Log mL)						
		0.92	0.42	0.33	-0.01	-0.10	-0.17	-0.40
1/2°	0°	1.05	1.25	0.97	0.99	0.64	0.90	0.85
	3/4°	0.72	0.62	0.62	0.55	0.64	0.64	0.85
	1 1/4°	0.73	0.55	0.74	0.55	0.64	0.64	0.85
	1 3/4°	0.65	0.55	0.56	0.55	0.64	0.64	0.85
	2 1/4°	0.63	0.55	0.56	0.55	0.64	0.64	0.85
1°	0°	1.48	1.39	1.54	1.38	1.60	1.42	1.42
	1°	0.85	0.71	0.76	0.58	0.64	0.64	0.85
	1 1/2°	0.74	0.63	0.71	0.58	0.64	0.64	0.85
	2°	0.72	0.55	0.58	0.55	0.64	0.64	0.85
	2 1/2°	0.65	0.55	0.56	0.55	0.64	0.64	0.85
2°	0°	1.84	2.66	2.35	2.98	3.16	3.36	4.35
	1 1/2°	1.01	1.07	1.32	1.31	1.55	1.78	2.02
	2°	0.83	0.89	1.04	1.25	1.45	1.43	1.56
	2 1/2°	0.78	0.93	1.02	1.05	1.30	1.25	1.52
	3°	0.79	0.85	1.01	0.99	0.98	1.12	1.57
4°	0°	3.10	3.37	3.56	3.90	4.16	4.39	7.21
	2 1/2°	0.80	0.77	0.81	0.86	0.81	0.93	1.56
	3°	0.80	0.84	0.82	0.72	0.93	0.69	0.85
	3 1/2°	0.83	0.74	0.74	1.30	0.81	0.78	1.09
	4°	0.81	0.78	0.66	0.63	0.78	0.64	0.85
6°	0°	3.61	3.36	3.79	3.70	3.72	3.77	4.88
	3 1/2°	1.00	0.79	0.85	0.68	0.78	0.71	0.85
	4°	0.83	0.79	0.65	0.58	0.64	0.64	0.85
	4 1/2°	0.84	0.69	0.65	0.55	0.64	0.64	0.85
	5°	0.77	0.55	0.56	0.55	0.64	0.64	0.85
8°	0°	4.18	3.68	4.47	4.18	4.52	4.88	6.26
	4 1/2°	1.05	0.86	1.03	0.73	0.64	0.67	0.85
	5°	0.90	0.64	0.73	0.55	0.64	0.64	0.85
	5 1/2°	0.73	0.56	0.56	0.55	0.64	0.64	0.85
	6°	0.78	0.58	0.64	0.67	0.83	0.64	0.85
10°	0°	3.78	3.91	4.08	4.20	4.87	5.49	7.54
	5 1/2°	1.01	0.84	0.88	0.80	0.86	0.76	0.85
	6°	0.88	0.87	1.10	0.96	0.86	0.89	1.77
	6 1/2°	1.19	1.14	2.05	0.68	1.59	2.06	4.21
	7°	0.99	0.91	1.02	0.91	0.86	0.97	1.99
60°		1.89	1.54	2.19	1.96	1.72	1.99	3.24

Median Response Time (secs.) For Eight Adapting Flash Areas,
Seven Display Luminances and Five Separations Between the Display
and Adapting Flash. Display Visual Acuity Requirement: 0.33

Observer: KBT

Table 5

Adapting Flash Area (Degrees)	Display - Adapting Flash Center Separation	Display Luminance (Log mL)						
		0.92	0.42	0.33	-0.01	-0.10	-0.17	-0.40
1/2°	0°	1.35	1.65	1.73	1.94	2.94	3.47	7.65
	3/4°	0.77	0.86	0.93	1.08	1.22	1.79	9.90
	1 1/4°	0.71	0.92	1.18	1.29	1.77	2.63	8.02
	1 3/4°	0.70	0.77	0.84	0.96	0.76	1.01	1.81
	2 1/4°	0.64	0.76	0.84	0.89	0.93	1.02	1.17
1°	0°	2.13	4.26	4.78	7.74	12.15	16.31	28.22
	1°	0.80	0.85	1.03	1.06	0.75	1.39	4.54
	1 1/2°	0.74	0.80	1.00	1.00	0.77	1.00	4.67
	2°	0.70	0.96	0.93	0.98	0.89	0.89	0.90
	2 1/2°	0.68	0.76	0.79	0.82	0.59	0.74	1.03
2°	0°	4.36	4.95	7.06	8.86	11.02	13.27	19.59
	1 1/2°	2.69	3.37	3.37	4.32	5.51	6.28	13.93
	2°	0.88	1.39	1.33	1.71	1.93	1.83	2.27
	2 1/2°	0.77	0.98	1.05	1.19	1.08	1.34	2.26
	3°	0.78	0.96	1.40	1.51	1.28	1.80	3.15
4°	0°	4.20	4.26	5.40	6.06	5.76	6.63	11.26
	2 1/2°	2.62	3.15	2.51	2.91	3.19	2.93	4.11
	3°	2.56	2.05	3.29	2.89	1.81	2.74	6.05
	3 1/2°	2.77	3.64	2.67	3.22	3.43	3.19	3.99
	4°	1.03	1.25	1.22	1.54	1.38	1.79	2.23
6°	0°	5.59	5.86	6.63	8.24	9.30	10.65	19.74
	3 1/2°	2.13	2.72	2.37	2.83	2.91	3.49	6.03
	4°	1.39	1.21	1.95	1.69	1.25	1.81	4.88
	4 1/2°	0.96	1.17	1.25	1.33	1.23	1.33	1.68
	5°	0.88	1.01	1.10	1.62	0.96	1.25	1.80
8°	0°	4.65	7.41	5.38	6.91	7.88	14.99	29.85
	4 1/2°	2.53	3.19	2.51	3.09	3.76	4.16	8.17
	5°	1.93	2.81	2.38	2.89	3.29	3.55	3.53
	5 1/2°	1.20	2.14	1.71	2.12	2.57	3.53	4.87
	6°	1.30	1.70	1.57	1.92	2.38	2.85	6.53
10°	0°	4.82	6.22	5.72	9.20	7.58	16.19	19.89
	5 1/2°	1.25	1.65	1.63	2.45	2.76	3.03	6.11
	6°	0.99	1.15	1.25	1.29	1.13	1.36	2.86
	6 1/2°	0.93	1.04	0.98	1.00	0.85	0.94	1.56
	7°	0.97	1.09	1.32	1.26	1.30	2.18	4.55
60°		4.70	5.09	5.16	6.27	6.78	8.72	14.97

Median Response Time (secs.) For Eight Adapting Flash Areas,
Seven Display Luminances and Five Separations Between the Display
and Adapting Flash. Display Visual Acuity Requirement: 0.33

Observer: PEM

Table 6

EXPERIMENT I

EXPERIMENT II

Flash Duration	165 μ sec	150 μ sec
Flash Luminance	3.8 log (mL-sec)	3.77 log (mL-sec)
Display Acuity	0.33	0.33
Display Luminance	0.00 log mL	-0.01 log mL
Observer	Median Response Time (secs)	
GTC	4.42	5.07
JHH	5.08	
GEM	5.17	
DIP		9.36
KBT		1.96
PEM		6.27
ALL Os	5.08	5.47

Table 7

Median response time for similar experimental conditions from two studies.

PHOTO STRESS TESTING AND MACULAR FUNCTION

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It's a pleasure to be here and address such a symposium as this. Since I began working with the effects of bright light on the eye in 1961, I have been pushing for some sort of a meeting in which the various investigators could pool their ideas and launch a coordinated research program. I think you will find my approach a bit simpler since I am an ophthalmologist. As an ophthalmologist, my basic interest is in understanding the milieu of the effect. Our basic interest is in retinal physiology, retinal health, retinal disease, and the effects of variations in retinal health on this process of flash blindness. Our concept of the effect of light upon the eye can be simply explained. If one takes a pre-adapted retina and exposes it to a quantitative flash of light, there is induced an alteration of threshold. We some years ago coined the phrase "photo stress" because to us, exposure to light in this manner is a physiological stress, much in the same fashion that an overdose of sugar is a physiological stress to the pancreas. We think that we can get information about the health of the retina from the manner in which it responds to this stress. We can also make some meaningful observations. This stress causes an alteration in the visual threshold, which Mrs. Miller described quite adequately. From this point on the recovery process is dependent upon the state of health of the retina. If there is normal cellular metabolism, we propose that there should be a return to the pre-adaptation threshold within a normal period of time. A normal period of time can only be defined by studying a normal population of the same age, so results must be based on studies of a normal population. If an abnormal physiological state exists (this can be of any variety), then there should be a prolongation of the return to this pre-adaptation threshold.

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We have been working with the following constants. We used a constant state of pre-adaptation, a control pupil size of 6 mm, a constant flash of 1200 lumens second per sq. ft. on the retina. We measured the recovery time to perceive a target that was 0.1 ft. lamberts in brightness. All the subjects were studied quite carefully from an ophthalmological standpoint. We tried to be very strict about our criteria of normality. A subject needed 20/20 vision, clear ocular media, acceptable fundoscopic examination, normal color vision, normal central fields, etc. Initially we wanted to know how precise this testing technique could be in a group of normal subjects. Table 1 shows the responses of a 53 year old white male. This subject was seen on three different occasions, for example, on the 9th of March; he was tested four times. Under OD are the responses for his right eye; under OS the responses for the left eye. March 14th he was tested four times again; March 17th he was tested twice. The mean recovery for the right eye was 62.8 seconds. This means that 62.8 seconds elapsed from the time of the flash until he could discriminate contrast of a 1/10 ft. lambert blinking target. Table 2 shows data obtained from a 27 year old normal white female. Her mean recovery for her right eye was 36.7 seconds; for the left eye was 35.8 seconds. I was very impressed as were those of us working on the project, at the tremendous consistency and reliability that a good subject could have. For example, I am a 44 second recoverer, and day in and day out I don't vary by more than 2 or 3 seconds in my recovery pattern. A good subject can do this. Now granted, in the course of testing and working with a large population, we have had a number of poor subjects and we have had to be very arbitrary in our decision about the subject's

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reliability. We have found that at least 90 to 95 percent of the people whom we tested who were under age 60, and who spoke English, were good subjects. The others we had to eliminate. To obtain data based upon a normal population, we studied 100 individuals. Fig. 1 shows the pooled data from 100 subjects. This shows a comparison of the right and left eyes, and in normal subjects there is no significant difference in recovery of the right eye and the left eye. Forty-nine of the subjects were tested on two different trials, two different dates, and again there was no significant difference in the subject's recovery on different dates. This of course is within a short period of time and not a period of years. When we plotted this data we found that the distribution was bimodal with the response of older patients being longer. In order to determine the significance of this observation, we arbitrarily divided the population into two groups, those under 40 and those over 40. Fig. 2 shows the differences in photo stress response as a function of age of the subjects. When we analyzed this information, we found that the difference in the mean recovery was significant. The mean for subjects under 40 was 50.7 seconds; for subjects over 40 it was 60.2 seconds. I think the important point in this figure is that while age 40 was used as an arbitrary point to dichotomize the data, we are actually dealing with an aging continuum. Retinal function, just as any other function in the body, goes through a cycle of birth, maturity and senescence. The rate of change of an individual's retinal physiology differs from person to person, and these changes are probably the results of differential hereditary, environmental and other factors that we don't yet understand. Up to age 20 or 30, there are not many individual differences. Starting at age 30, vision will begin to

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change at various rates of speed. Working with the normal population, we demonstrated several points to our satisfaction. The first was that we had a process that could be adequately studied with simple instrumentation. The second was that in normal individuals recovery measurements are consistent from day to day. The third was that there was no difference in the recovery time between the two eyes. There is, however, a considerable inter-subject variability and at least one of the factors involved in this is the age of the subject. Now, what happened when we began to study patients who had retinal disease? At this point it becomes quite fascinating. The first example that I will show you is a rather obvious case that we chose. This was a 30 year old male who had a healed scar in the left eye from an old episode of chorioretinitis. He had a permanent amblyopia as it were, an obvious pathological problem. His vision in that eye was 20/100, his vision in his good eye was 20/20. We tested him a number of times and found that the normal eye recovered in about 50 seconds. The eye with pathology required almost twice as long to recover (Table 3). We did this not because we were surprised at the findings but to demonstrate that with a static disease process, we could demonstrate a static recovery pattern. He had a dissimilar pattern for the two eyes and the results could be analyzed and compared to our normal population. The recovery time for the subject's left eye was abnormally long, while the recovery time for the subject's right eye fell within the normal population. Thus, we now have a method to statistically analyze the subject's responses and determine whether or not the individual eyes are normal. In this case the disease was obvious and we did this as an exercise to prove our technique. I would like to present a second case that is quite

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interesting. I saw this patient when I was in my last year of residency and he came to us with very minimal symptoms. He had noticed some haze in his visual field, but had no other complaints. He had a clinical picture that for want of better knowledge we called histoplasmic chorioretinitis. We think this is related in some way to histoplasmosis but we are not certain how. He had perifoveal lesions in each eye. These were deep to the retina; the foveas themselves were quite normal; his vision was 20/20 in each eye and he said his symptoms were quite minimal. When we first saw him on October 6th, his vision was 20/20 in each eye, and if you did not see the lesions, you would have said that he was normal. When we tested him at this time, the right eye required about 90 seconds for recovery; the left eye slightly less. Comparing these recovery times with those of our normal population, his recovery was found to be abnormal. At this point we could say that this was significantly different from other individuals of his age (Table 4). The next time we saw him on October 12th, the vision had changed a little bit, it no longer was 20/20 but it wasn't that bad; it was 20/40 in the right eye and 20/25 or slightly better in the left. However, the recovery times became much longer. Something very tragic was going on in this man's eye and it wasn't revealed to us by ophthalmological examination or by checking his vision. Since most of us would pass 20/20 and 20/25+ as being about the same, and 20/20 to 20/40 is not an astounding difference, the only real indication of disease was that his recovery time almost doubled. In the next three times that he was seen, his visual acuity did not change at all, and indeed the appearance of the lesions in his eye did not change significantly. However, his recovery duration became more and more prolonged, indicating to

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us that there was some progressive degeneration occurring, probably edema. Thus, an active degenerative process was taking place in this man's retina, destroying retinal function. This change in function anticipated the eventual outcome of this man's disease since the disease progressed, finally resulting in complete loss of central vision in spite of all attempts at treatment. By March 4th he had essentially lost all foveal vision in his right eye and was losing it in his left eye. He eventually became legally blind with no foveal vision in either eye.

One other problem I'd like to show you is one in which I have been quite interested. One of our major problems in ophthalmology today is the diagnosis of the effect of drugs upon the retina. There are several drug groups that are involved which have serious effects; one of them is the chloroquin group of derivatives. These compounds, as you probably know, were used for malarial treatment, however in recent years they have been used for the treatment of collagen diseases. I don't think anyone knows quite what the action mechanism is, but they do offer some degree of symptomatic relief. One of the unfortunate side effects of chloroquin toxicity is retinal degeneration, at least in the doses that are used for treating collagen diseases. Unfortunately we have no test at present that can detect the effects of chloroquin on the retina prior to visual loss. Once vision has been lost we know there has been trouble but then it's too late. If you recall, we said that recovery is based upon the integrity of the physiological processes, and if we have a situation where a drug is causing a toxic effect, and the chloroquin effect is probably in the alcohol dehydrogenase systems of the retina, it's probably in the retinal oxidative mechanisms. We should thus be

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able to study the effects of these drugs upon retinal functions. If recovery is dependent upon effective regeneration of visual pigment, and if the drug is causing impairment of this regeneration, then a kinetic test such as the photo stress test in which one studies a patient over a period of time and measures their recovery patterns should be a sensitive measure of the deterioration of visual functions. The patient to whom I have referred was a 56 year old white female who had received a total dose of only 50 grams of chloroquin up to the time of testing. Her vision was 20/20 in each eye and was clinically normal, i.e., she had normal color vision, and all the other clinical criteria for normality were met. Her mean recovery time was well over 100 seconds for each eye. A hundred seconds for each eye is definitely an abnormal recovery time. Up to this point no one has been able to satisfactorily demonstrate retinal toxicity in patients who have received less than a total of 100 grams of chloroquin.

In summary now, what I've attempted to do is put this problem into a perspective from the medical or ophthalmological viewpoint. Flash blindness, a phrase that I don't particularly like, cannot be understood without an understanding of the basic physiology of the retinal processes and without understanding the mechanisms that are responsible for it. Flash blindness research is unlike the research involved in retinal burns where the problem is somewhat simpler. Here you're working with a purely physical model. Your problems are really ones of thermal measurement, image size and ocular transmission. If you know these factors, and perhaps the density of pigment in the retina, you can determine retinal burn threshold. In flash blindness, or glare recovery, we're dealing with a problem that is predicated upon understanding the basic milieu of the retina, and any alterations

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in retinal health and retinal function will affect recovery. Therefore, any model that has to be workable has to consider not only the parameters of exposure time, intensity level and retinal image size, but also the relative efficiency of the subject's retina. This efficiency definitely varies with age and with the subject's genetic pattern. In the course of our testing we have seen some very interesting cases. One for example, was referred to us at the Bascomb Palmer Eye Institute by a very astute ophthalmologist in Miami. He had seen her sister and had been following her sister for some 15 years. Her sister when he had first seen her had had a retinal appearance much like the lady he referred to us. Very minimal findings but some question of being abnormal. Her sister went on over a period of time to develop a frank and rather bizarre hereditary macular degeneration. The normal sister, who had an appearance that was suggestive of the other sister 15 years previously, had 20/20 vision and was clinically normal. However, when we tested her, her recovery for each eye was over 120 seconds. This is almost twice the norm for someone her age (she was in her forties). We interpreted this to be the indication of a very striking metabolic defect, which at this point, had not become clinically pathological. This is the sort of patient we like to follow, since if our predictions are correct, she should develop a similar macular disease.

Table 1. Testing Results of 53 Year Old White Man

Visual Acuity	Date	OD	OS
20/20 OD	Mar 9	57.1	52.9
		63.2	57.3
20/20 OS		62.6	50.1
		63.4	57.3
Mean	Mar 14	60.4	62.4
		58.2	61.7
62.8 OD		63.8	62.3
		64.2	66.2
59.9 OS	Mar 17	67.1	64.0
		68.7	65.2

Table 2. Testing Results of 27 Year Old White Woman

Visual Acuity	Date	OD	OS
20/20 OD	Dec 10	44.5	42.2
		42.9	38.3
20/20 OS		34.4	34.6
	Dec 11	40.0	38.8
Mean		33.6	31.4
		34.2	41.0
36.7 OD		31.0	30.1
35.8 OS	Jan 8	39.1	35.0
		34.4	36.5
		33.7	31.0

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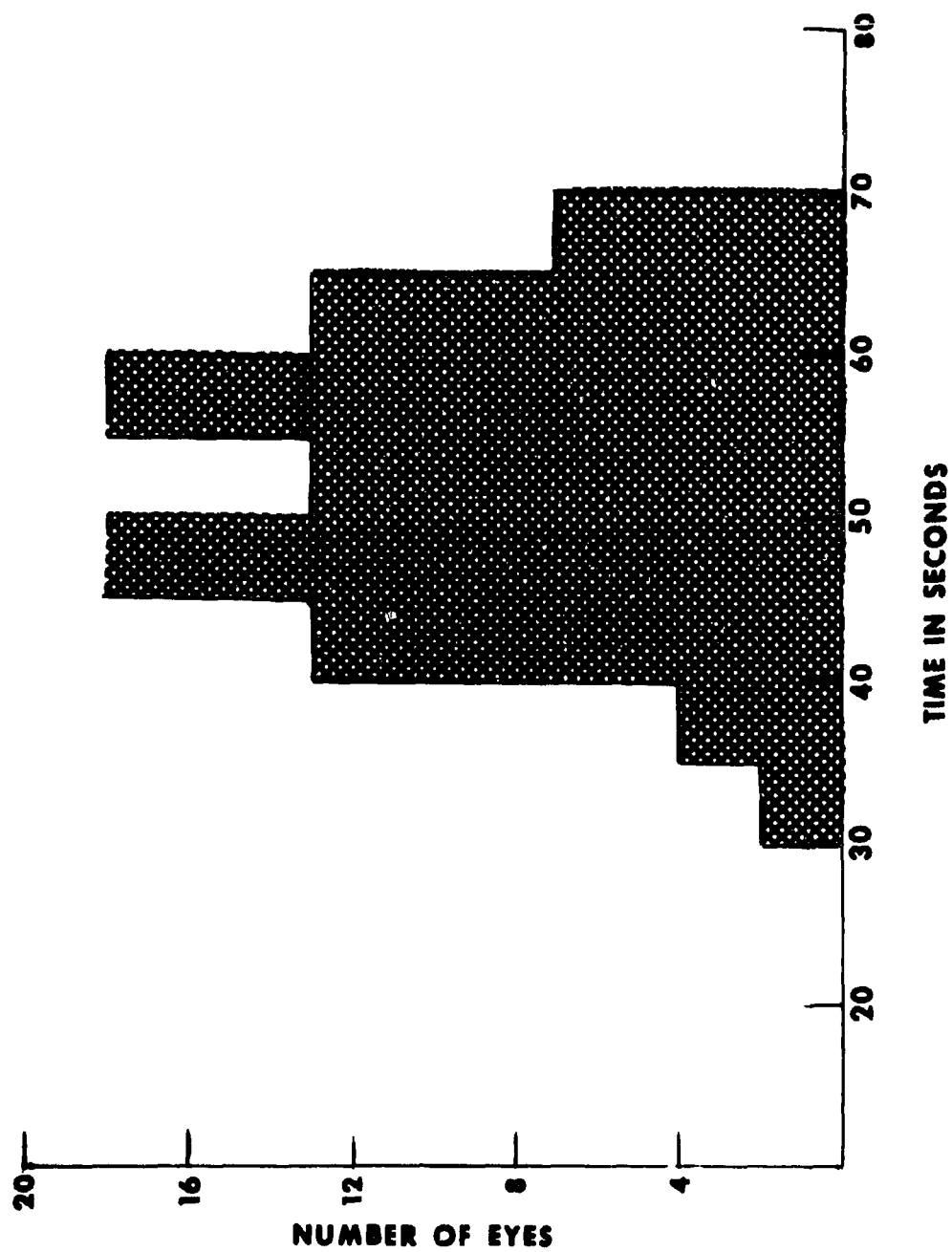
Table 3. Macular Scar - OS

Visual Acuity	Date	OD	OS
20/20 OD	March 11	53.1	114.1
		49.7	116.1
20/100 OS		57.2	113.4
	March 20	49.6	109.2
Mean		52.5	107.4
50.8 OD	March 23	44.3	106.7
		50.6	110.3
111.7 OS		52.1	112.7
	March 25	54.9	112.4
		44.0	115.1

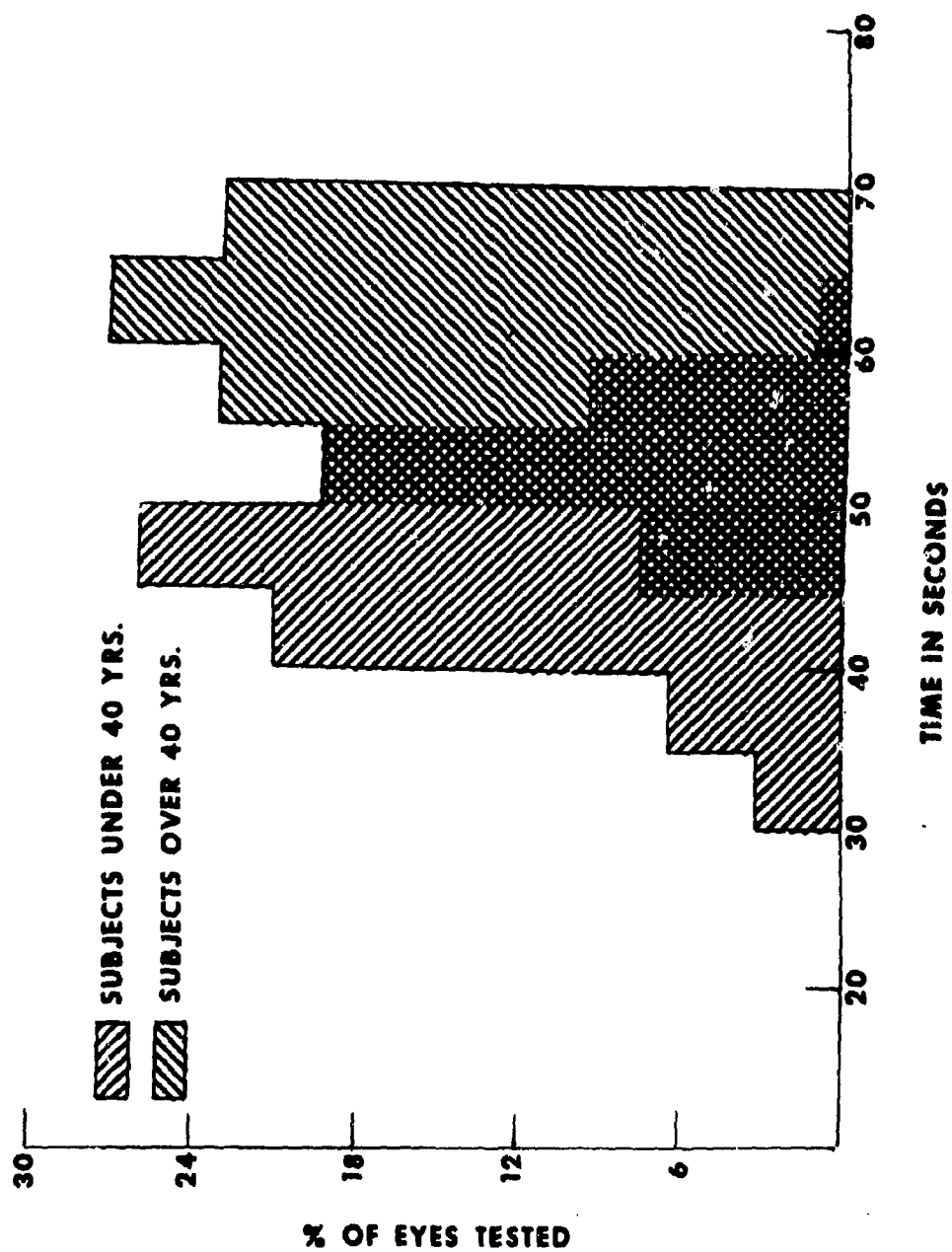
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Table 4. Posterior Uveitis - OU

Visual Acuity		Date	OD	OS
20/20	OD	Oct 6	87.2	87.8
20/20	OS		91.2	86.9
20/40	OD	Oct 12	184.2	117.9
20/25 ⁺²	OS		170.7	123.7
20/40 ⁻²	OD	Oct 18	220.9	100.0
20/25 ⁻²	OS		226.7	94.6
20/40 ⁺²	OD	Dec 21	276.5	128.7
20/30 ⁺¹	OS		268.7	132.6
20/400	OD	Mar 4	255.3	165.9
20/100	OS		262.7	174.3



1. Normal photostress response.



2. Normal photostress response. Comparison of age.

LOW SINGLE CELL RESPONSES AS A FUNCTION OF INTENSE LIGHT FLASHES
A PRELIMINARY REPORT

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INTRODUCTION

As an early speaker in this Symposium, it would be unkind for me to review the research that has been done on the recovery of visual function from high intensity light flashes. Other participants have been more closely associated with this work and will undoubtedly cover these past efforts. Therefore, these efforts shall be alluded to, but research involving the electrophysiological monitoring of neurophysiological responses will be stressed.

The visual recovery problem following exposures to intense light stimuli has been studied by both the applied and the theoretical researcher. The applied laboratory has attempted to establish the time of visual recovery following the flash and, in addition, provide protection for the visual system. The theoretical investigator was interested in the psychophysics and, primarily, the visual pigments and their relationships to the reciprocity law. These statements are not intended as criticisms of either group, but to demonstrate different approaches to the solution of the same problem. In fact, both approaches have provided additional valuable information to the literature. For example, one who is interested in the visual pigment-reciprocity law relationships could undoubtedly recommend the design of excellent protective devices if these relationships were fully understood. Likewise, those who have established recovery times, tried protective devices, and searched for better protection have aided substantially in gaining an insight to the solution of the problem.

The electrophysiologist has been rather slow in utilizing his techniques in studying the effects of high intensity light flashes

on the visual system. This may be defended because he has been trying to establish normal data for the usual light intensities before higher intensities are approached. He is usually interested in spike frequency, spike patterns, and mutually exclusive excitation-inhibition systems and how these systems provide meaningful information to organism. Therefore, it may appear that the neurophysiologist may be trying to study something other than flash blindness while he is attempting to unlock the information code of the visual system.

An example of the value of electrophysiology research may be briefly given. The sidewinder air-to-air missile concept was derived from the pit viper electrophysiological research. Predictions on the trainability of the vestibular system have been made by Dowd¹ and Cramer et al² based on single cell responses of the cat vestibular nuclei. The ideal situation would be a team including those interested in psychophysics, photopigments, neurophysiology, and protective devices to work cooperatively on the problem.

Einthoven and Jolly³ were probably the first to use intense stimuli in the study of the ERG in the frog's eye. With a 120×10^6 m-cd stimulus, the a wave was very large and the b wave reduced as the eye became light-adapted. Cobb and Morton⁴, in humans, found a 4-7 msec ERG latency and a notching of the first three phases of the waveform for 56×10^4 ft.-L. flashes. More recently, animal ERG's were used to study dark adaptation in animals after short flashes of high intensity light⁵. The dark adaptation recovery curves were divided into three phases rather than the usual two-phase curve. The initial phase was attributed to neural adaptation. The second and third phases were attributed to resynthesis of the photopigments.

For the animals studied there was a general rise in the threshold of the ERG with the same flux density as the pulse length increased.

Jacobs⁶ adapted the squirrel monkey to different levels of luminance (21.1 cd/m^2 maximum). Several interesting features were found from LGN broad band excitatory and inhibitory cells. The nature of the response depended on the luminance of adaptation stimulus, i.e., a cell may fire when adapted to one level but show inhibition on adaptation to another level. The spontaneous discharge rate was related to the adaptation luminance. Excitatory cells increased spontaneous discharge rate as adaptation luminance increased, but the reverse was found for inhibitory cells. Further, the range of brightness discrimination was over only a ± 1 log unit range.

Visual cortex responses to a 1000 joule flash bulb, 15 cm from the cat's eye, have been described by Robertson and Evans^{7,8}. The firing rate of cortical single units increases to a high peak after 10 minutes and declined to the control level after 30 minutes. Repeated flashes produced steplike increases in the firing rate which persist for up to 2 hours. Further, this phenomenon was not due to maintained retinal activity but was cortical. Discussion was given to show that the increased frequency of firing of the cell was within bursts and not to the increased length or frequency of the bursts.

The purpose of this paper is to present preliminary data on the response of the lateral geniculate nucleus single units to intense flashes of light.

APPARATUS AND PROCEDURE

Apparatus

An optical stimulator (Fig. 1) designed for retinal ganglion cell research was used to deliver square wave light stimuli to the eye.

The stimulator consisted of two integral optical systems. Source S_2 could serve as a background illuminator but was not used during these experiments. The stimulus light came from source S_1 , was collimated by lens L_1 , passed through filter holder FH_1 , and was brought to focus at aperture A_1 by lens L_2 . The stimulus source intensity could be varied by ND filters placed in FH_1 or by the neutral density wedge NDW. From A_1 the beam was collimated by lens L_3 and passed through apertures A_2 and A_3 . Lens L_4 focused the light beam in the entrance pupil of the eye.

Apertures A_2 and A_3 deserve special description. Each consisted of 16 separate apertures in two wheel like discs. In disc A_2 the largest aperture was 14 mm in diameter. The other apertures contain circular opaque centers of 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.75, 0.50, 0.34, and 0.25 mm in diameter. The apertures in disc A_3 are 14, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.75, 0.50, and 0.34 mm in diameter. The discs were constructed so that their apertures would lock in position and automatically self-center in the optical beam. Thus, multiple spot and annular stimuli could be readily obtained. In these experiments both A_2 and A_3 were set at maximum (14 mm).

Shutter S was constructed of a thin aluminum strip epoxied to a speaker coil. It provided a silent light chopper at the 1 x 4 mm aperture A_1 . The shutter was controlled by Tektronix 160 series waveform and pulse generators. It furnished a square wave-light pulse with a 2.5 msec rise time and a 3.0 msec fall time. A light-dark ratio of 50 percent and a 2-second pulse length were used throughout the experiment.

A slight modification to the optical stimulator was made for

these experiments. Mirror M_2 was removed and the beam focused directly into the animal's eye in Maxwellian view.

Source S_1 was a 6.0 volt, 2.5 ampere, tungsten bulb powered by a 6 volt DC battery. The photometric intensity of the optical stimulator source was calibrated by the method described by Westheimer⁹. The maximum luminance of the source at the plane of the pupil was 2.8 mL. This provided a retinal illuminance of 1.12 lumens/steradian. The irradiance of the source, incident on the cornea, integrated over 400 to 700 nm, was calculated to be approximately 2.76×10^{-6} cal/cm²-sec.

A Strobunar 65-C xenon flashlamp was used as the flash blindness source. Its calibration procedure was as follows: An SD-100 photodiode was calibrated against an NBS standardized Eppley thermopile and the following relationship obtained:

$$H \left(\frac{\text{uW}}{\text{cm}^2} \right) = 0.385 \text{ Vpd} \left(\frac{\text{uW}}{\text{mv-cm}^2} \right)$$

where H was the irradiance and V_{pd} the voltage output of the photodiode. The 65-C was mounted 170 cm from the photodiode, and its output was attenuated by two stainless steel and two copper wire neutral mesh screens to prevent saturation. The transmission of each of the stainless steel and the copper filters was 31.0 percent and 29.0 percent respectively. Therefore, the total transmission through the four filters was 0.81 percent.

The output of the photodiode was displayed on a Tektronix 502 oscilloscope and photographed (Fig. 2). The average pulse width was 1.75 msec. The effective area of the 65-C was 18.1 cm². The average voltage from the photodiode was 6.916×10^5 mv. Therefore, the radiant emittance W was calculated to be 86.44 cal/cm²-sec at the source.

From the expression

$$H = \frac{U}{At}$$

H = irradiance

U = energy in calories

t = pulse duration

one may calculate the irradiance at any distance since U is independent of distance. For the irradiance at the cornea

$$W = \frac{U_s}{A_s t_s} \quad \text{and} \quad H_c = \frac{U_c}{A_c t_c}$$

the following relationship holds:

$$U_s = W A_s t_s \quad \text{and} \quad U_c = H_c A_c t_c$$

but $U_s = U_c$ and $t_s = t_c$

therefore $H_c = \frac{W A_s}{A_c}$

H_c = irradiance at cornea

W = energy at source

A_s = area of source

A_c = irradiated area at the cornea

The irradiance on the cornea was 3.2 cal/cm²-sec. For those who desire to calculate the energy on the retina, the average dilated pupillary diameter for the cat is 14.6 mm. Vakkur and Bishop¹⁰ and Vakkur et al¹¹ give additional optical constants for the cat's eye.

Procedure

The cat, Felis domestica, was used as the experimental animal. The animal was anesthetized with 25 mg/kg body weight Nembutal, placed in the stereotaxic, and surgery performed. The animal was then Flaxedilized and placed on the respirator with a volume/stroke of

15 ml/kg and a respiratory rate of 20/min. The animal was maintained on constant anesthesia and paralysis by continuous intravenous infusion of 4.2 mg/hr Nembutal and 20 mg/hr Flaxedil in Ringer's solution delivered at the rate of 4.5 ml/hr.

The eyes were fully dilated with 1 percent atropine sulphate and 10 percent phenylephrine HCl eye drops. Plastic contact lens ERG electrodes were fitted to both eyes. The animal was placed in a Faraday box and the stimulus light aligned in Maxwellian view.

Tungsten microelectrodes¹² with tip diameters of about 0.5 μ were used throughout the experiments. The electrode was lowered through the brain to the lateral geniculate nucleus (LGN) until a single cell response was obtained. The response was identified as LGN extracellular, Type b or c, according to the criteria of Bishop et al.¹³. Two different methods were used in locating the single cell spike potentials. One method was to localize the cell as it spontaneously fired. The second involved locating the cell while the visual stimulus was given. Either method satisfactorily isolated a cell for further study. After the preparation had stabilized, the cell was classified as ON, OFF or ON-OFF according to its response to the maximum intensity of the visual stimulus. It was not unusual to maintain a cell for 6 to 8 hours.

The single unit spike responses were fed through a cathode follower to a low level DC preamp and simultaneously displayed on a Tektronix 502 oscilloscope, a loud speaker system, and a tape recorder. The spike responses were photographed from the face of the CRO by a Grass Kymograph camera for further analysis.

The experimental protocol used for a given cell may be described

as follows: After a single unit in the LCN was isolated, its spontaneous light response was recorded; that is, its response to the steady state stimulus light through an NDO.0 filter. The animal was dark adapted and spontaneous dark responses were obtained. The firing response of the cell was then determined to progressive attenuation of the light stimulus in 0.5 log unit steps until the spontaneous dark firing rate was reached.

The cell was flash blinded with the strobe light, and the cell's response was recorded at each different visual stimulus attenuation step. The routine for each ND filter was stopped when the auditory firing rate returned to the preflash level. Approximately 20 minutes of dark adaptation was allowed before the next flash was delivered to the eye and another visual stimulus intensity response obtained.

Two shortcomings of this protocol became evident after a few experimental sessions. The auditory system was found to be a very poor absolute counter if one depended on the memory of a previous firing rate. Thus, the routine was stopped almost invariably before the firing rate of a cell returned to the preflash level. Second, photographic recording of the spikes required a 100 mm/sec film rate. This amount of film took up to four months for analysis. We have recently purchased a CAT computer and a counter which will allow better experimental procedures and more precise analysis of the data.

RESULTS

Graphic data of spikes per stimulus are presented for an ON cell, an OFF cell, and an ON-OFF cell. To date, approximately 30 different cells have been studied, but average data do not appear to be a good presentation method because of the wide variability in firing rate between cells of the same type.

The number of spike responses was counted for each light and dark portion of the square wave visual stimulus. The ON and OFF spike counts were meaned over 5, 10, or 20-second periods of time after the flash was given. These mean spike counts are plotted in time against the number of spikes per stimulus. Even though mean spike counts were used, the shape of each curve was maintained. Time interval variations were used only to allow presentation of the data over the different periods of recovery time. In each of these graphs the spike count per stimulus prior to flash is shown at zero time and not joined to the postflash spike count. This preflash spike count can be used to determine the adaptation of the cell.

Fig. 3 presents the spikes per stimulus from an ON cell for different levels of attenuation of the stimulus intensity. Figures 4A through D show the recovery time of the cell to the light flashes. The intensity of the visual stimulus was at maximum, then reduced log -1.0, -2.0, and -3.0. Data were taken for this cell in 0.5 log unit steps to log -4.0, but these are representative data.

The spike response of an OFF cell for different stimulus intensities is shown in Fig. 5. This cell was difficult to classify since it gave ON responses at lower levels of stimulus intensity but was called OFF since our classification criteria was based on responses at ND 0.0. Fig. 6 shows the different responses of the OFF cell to flash No. 1, lower; flash No. 2, middle; and flash No. 3, upper. The responses of the same cell to log -0.5, -1.0 and -1.5 relative stimulus intensity after flash No. 1 are shown in Fig. 7, lower, middle and upper, respectively.

The ON-OFF spike responses for different visual stimulus intensities are shown in Fig. 8. The recovery of the ON-OFF cell to

flash No. 1 is given in Fig. 9 for relative stimulus activity of log 0.0, lower curve, and log -1.0, upper curve. The same recovery data for relative visual stimulus intensity log -1.5, lower curve, and log -2.0, upper curve are illustrated in Fig. 10. The ON-OFF spike responses for flash No. 2 are shown in Fig. 11. In this graph the log relative visual stimulus intensities are log 0.0, log -1.0, log -1.5 and log -2.0, from bottom to top, respectively.

DISCUSSION

It should be emphasized that the data are preliminary and many statements made in the discussion are not definitive but subject to alteration with further research.

Many cells failed to show a spontaneous activity. Lower spontaneous activity was found when using the stimulus to localize a cell than when localizing a cell without the stimulus. Bishop et al¹³ found only a 37 percent spontaneous activity of 137 cells studied. The most common spontaneous activity consisted of groups of 3 to 5 short high frequency bursts, but occasionally groups of bursts fired at regular intervals. Another type consisted of short rapid bursts of spikes followed by a long period of silence; then a sudden burst of activity would reappear. This type of activity was so startling that timing of the sequence was not done. The last type of spontaneous activity was single spikes occurring at regular intervals, as high as 25 spikes per second. The spontaneous activity appeared to either disappear or synchronize with the light stimulus when it was on. One is referred to Bishop et al¹⁴ and Levick and Williams¹⁵ for references and a discussion on the significance of the characteristics of the LGN spontaneous activity.

The most startling finding was that the classical ON, OFF, and ON-OFF cell classification did not hold at different levels of adaptation. The ON cell gave OFF responses; the ON-OFF cell changed to give ON and OFF responses. The relative magnitude of the spike response changed with each level of visual stimulus. This was first thought to be a new finding, but Donner and Willmar¹⁸ reported similar reversals to higher intensities of the stimulus for the ganglion cell. These findings seriously question the validity of classifying cells without specifying the adaptation level and stimulus intensity.

One of the most important questions raised in these studies is just what or how is the information conveyed from the LGN to the visual cortex. The ON cell, at highest visual stimulus, shows a complete reversal after the flash and gives OFF responses. This pattern persists for 15 to 20 seconds before the cell reverts to higher ON than OFF responses. Even then, the ON firing rate is about half its original rate. If the stimulus level is decreased by an ND 1.0 filter, the ON firing rate is almost 4 times normal at 60 seconds after the flash. If information is conveyed by the number of ON impulses, it appears that excessive information would be given at ND 1.0 stimulus intensity. All other levels of stimulus intensity appear to add even more confusion to the system.

The OFF cell showed a general reversal of the ON-OFF firing ratio with decreased stimulus intensity until at ND 1.5 the ON response is predominant. Additional flashes at ND 0.0 stimulus show undulating crisscrossing of the OFF-ON cell firing (Fig. 6). It is interesting that these change-over points occur at approximately the same time intervals but are more prominent as the number of multiple flashes

increases. One OFF cell studied remained silent for 17 minutes after a flash and returned to the preflash firing rate abruptly.

Changes in firing ratios are also evident in the ON-OFF cell. The amount of time this cell was studied was considerably less than the other cells so good comparison cannot be made.

The ON-OFF cell is the only one presented which was flashed twice and studied at all stimulus levels. The only apparent change brought on by the second flash is that at the highest intensity level (ND 0.0, Fig. 11) the spikes per stimulus correspond to its original firing level. Other stimulus levels for flash No. 2 show markedly reduced firing rates and crossing of the ON and OFF response curves.

If one uses the cell's firing rate or ratio of firing rates as a criteria, it appears that the spike response varies greatly with the level of adaptation and stimulus intensity. At the same time, the LGN system demonstrates adaptation to its environment and provides some information which might be meaningful in spite of the intense flashes. Barlow et al.^{17,18} describe changes in the receptive fields that occur during dark adaptation. The surrounding zone of the dark adapted receptive field disappears and only "on" or "off" central responses occur. In light adaptation the surround always gave an opposite response to the center of the receptive field. They also found some parts of a receptive field which reversed their contribution to the ganglion cell. One explanation of our reversed findings is that when flashed with an intense flash, the receptive field reversed its response to the stimulus. Thus, as the cell dark adapts, normal ON, OFF, or ON-OFF responses reappear. The significance or the intensity level required to produce this reversal is

not known, but Evans and Robertson^{7,8} have shown prolonged excitation effects in visual cortex single units.

In summary, the responses of ON, OFF, and ON-OFF single units in the LGN to intense flashes have been given. The full significance of the changes manifested is not known. Comparison of this data with other high intensity data shows that considerable disruption of the "normal" occurs. It was suggested that receptive field adaptation effects might explain the reported phenomenon. We have planned future experiments to test this and other hypotheses.

CERTIFICATE

The animals involved in this study were maintained in accordance with the "Guide for Laboratory Animal Facilities and Care" as published by the National Academy of Sciences, National Research Council.

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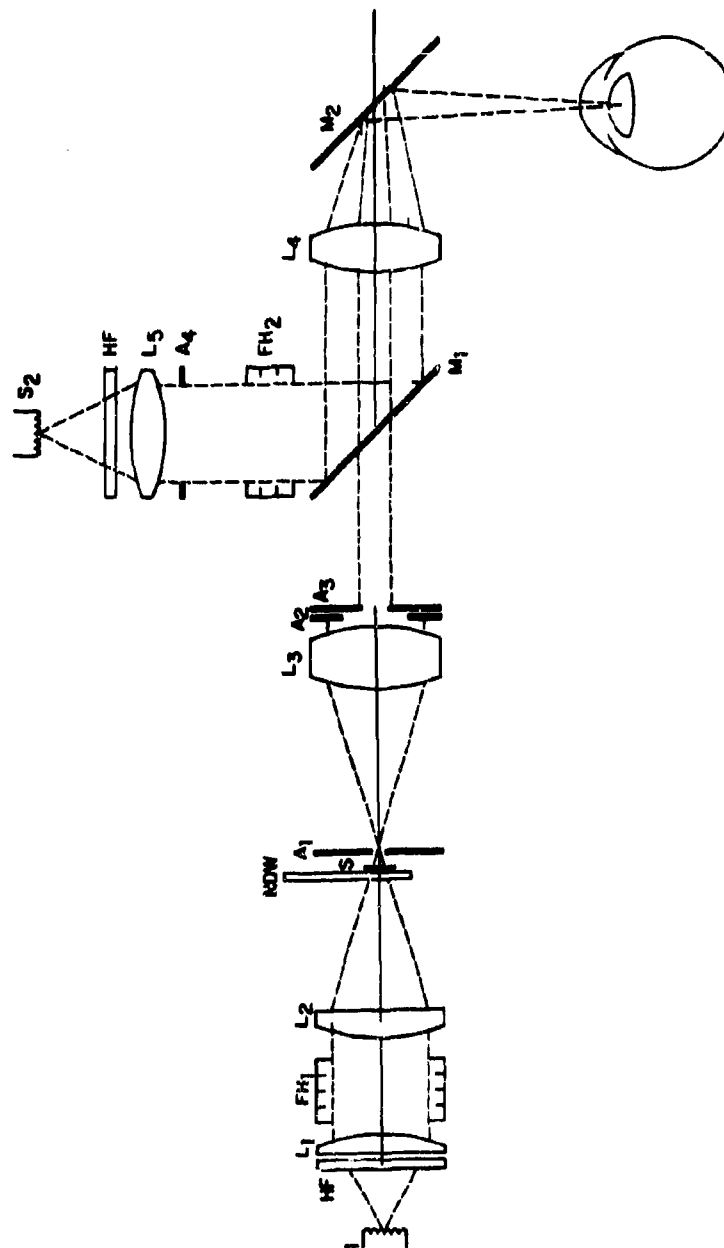
This study was partially funded under Project 5710, Subtask 03.003, by the Defense Atomic Support Agency.

The author wishes to express gratitude to A1C George D. Jones and A2C James E. Strong for assistance in conducting these experiments. The author is indebted to Mr. Kenneth R. Kay for source calibration data.

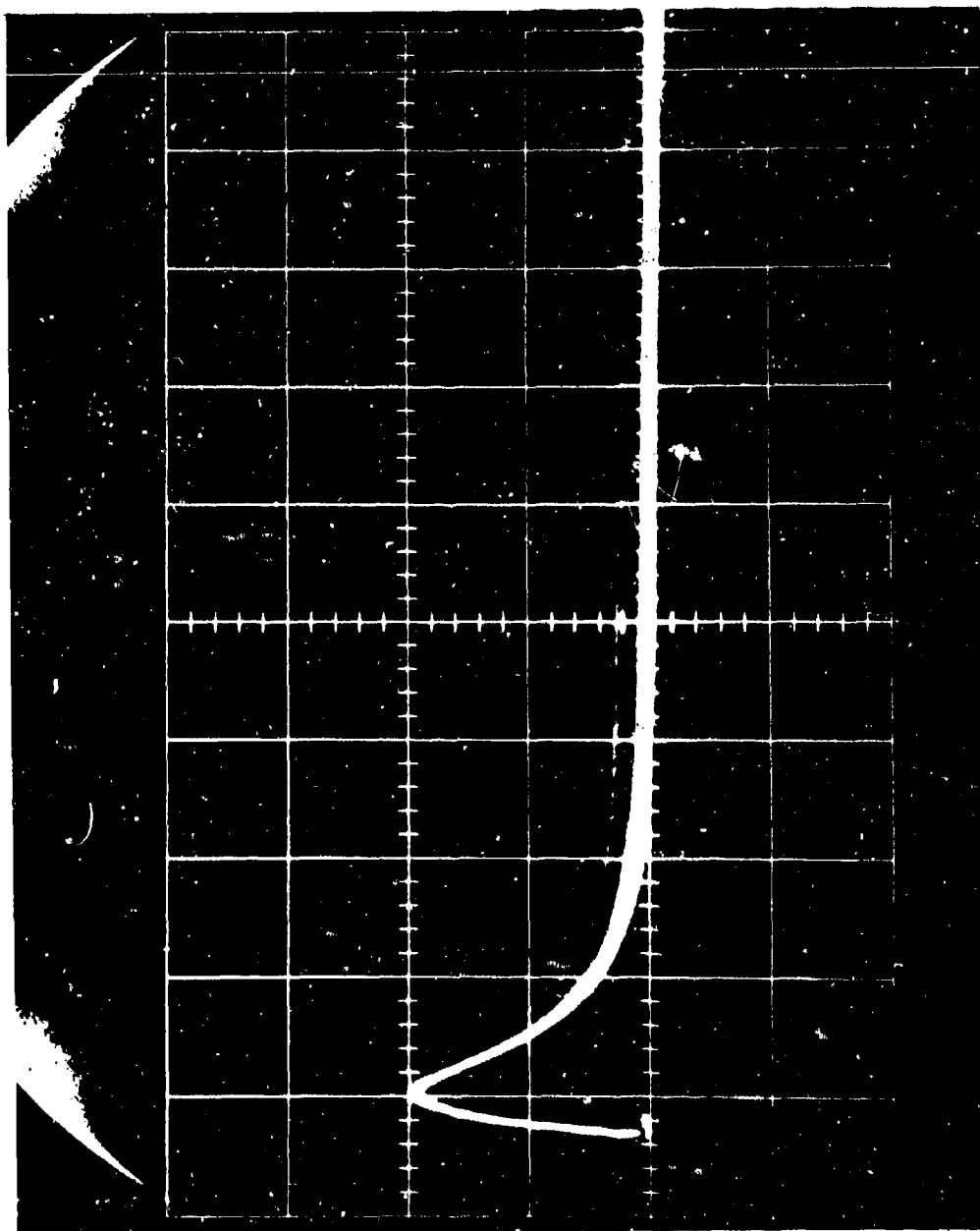
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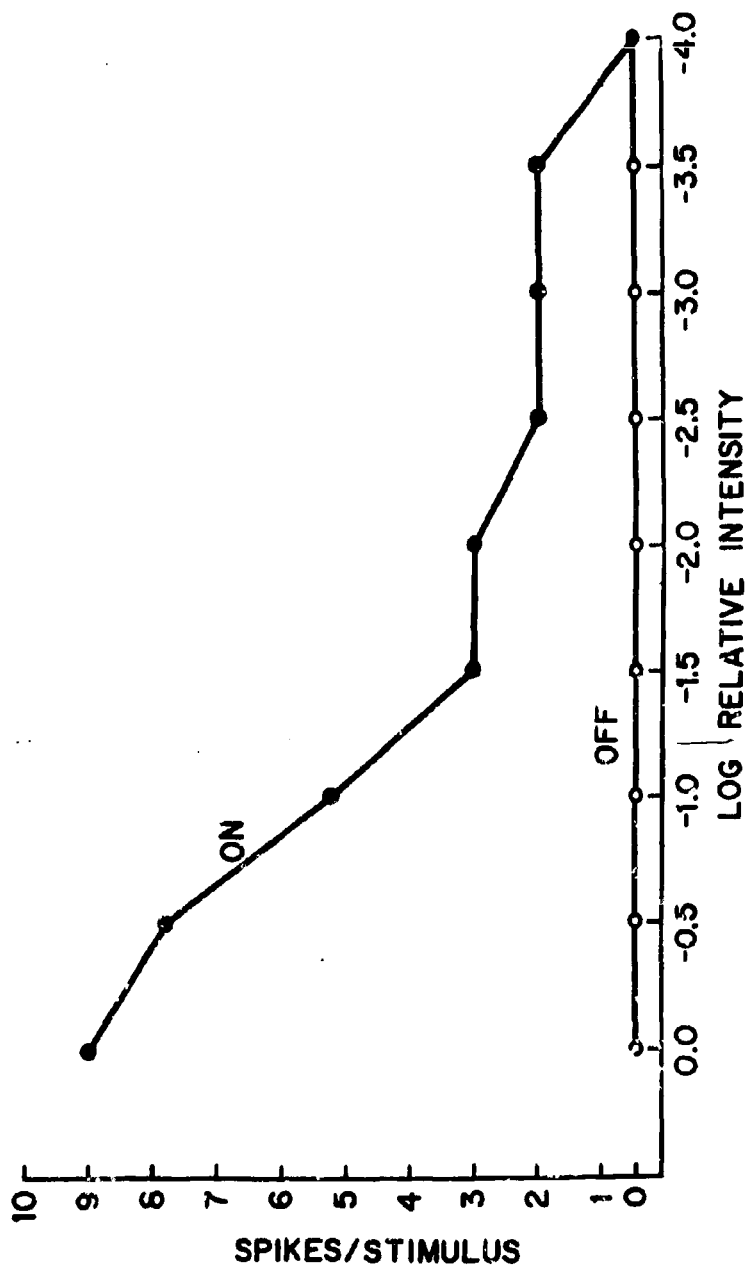
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1. Schematic diagram of the optical stimulator used to deliver square wave light stimuli to the eye.



2. Output trace of the photodiode as displayed on a Tektronix 50P oscilloscope.



3. Spikes per stimulus from an ON cell for different levels of attenuation of the stimulus intensity.

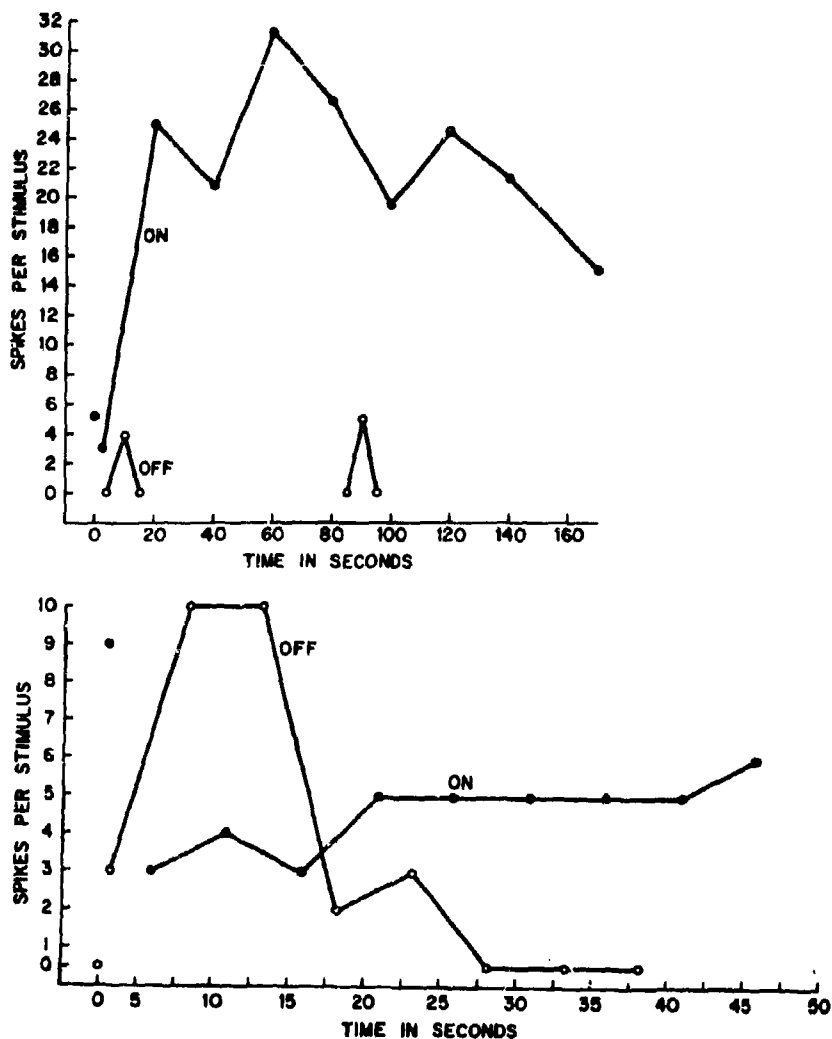


Fig. 4 A and B

The recovery time of the ON cell to the light flashes. The intensity of the visual stimulus was at maximum, then reduced log -1.0, -2.0, and -3.0. Data were taken for this cell in 0.5 log unit steps to log -4.0, but these are representative data.

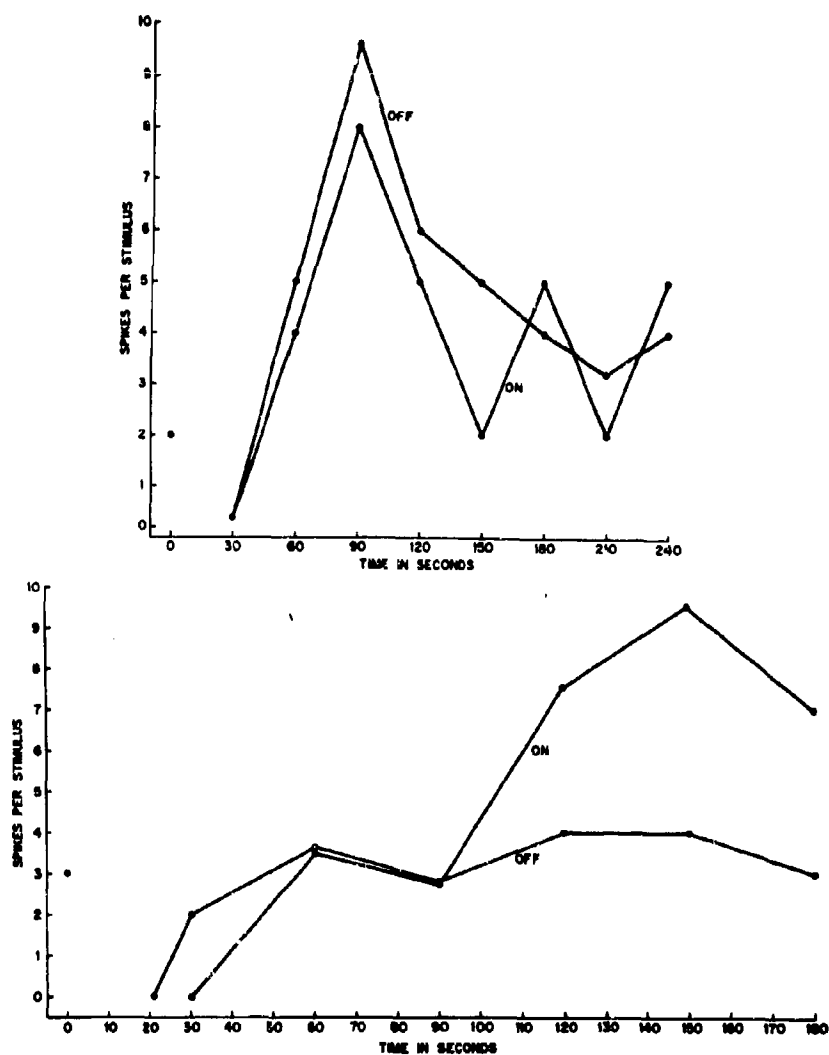
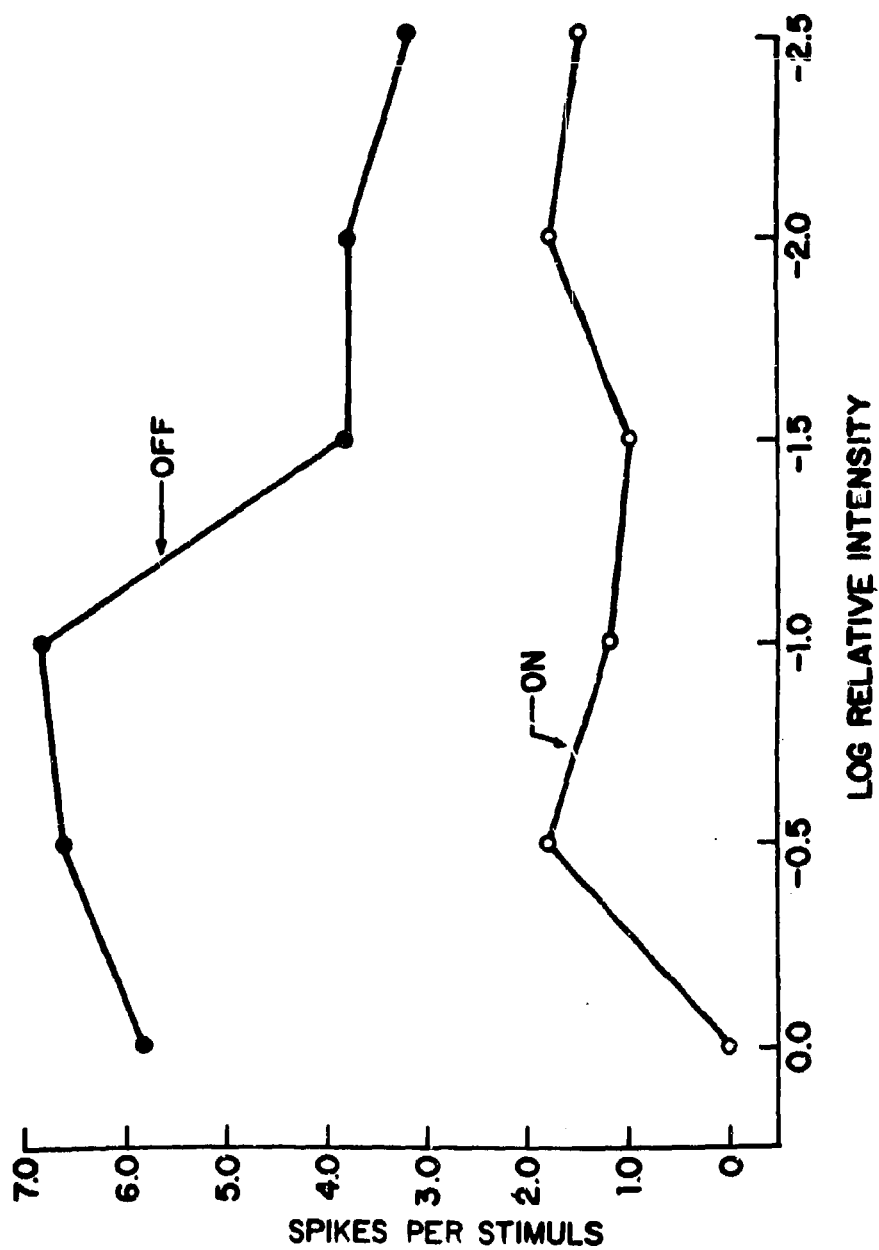
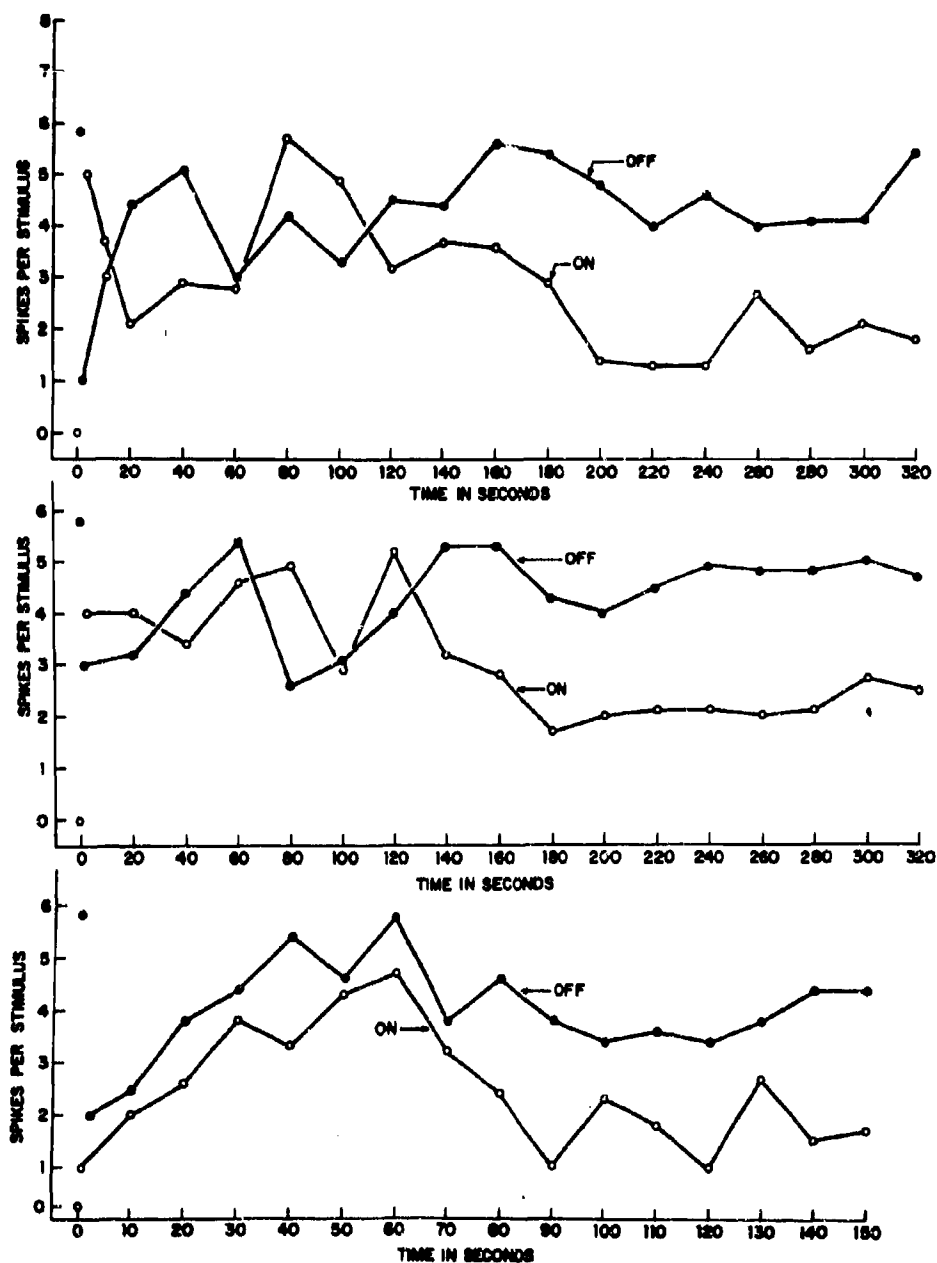


Fig. 4 C and D

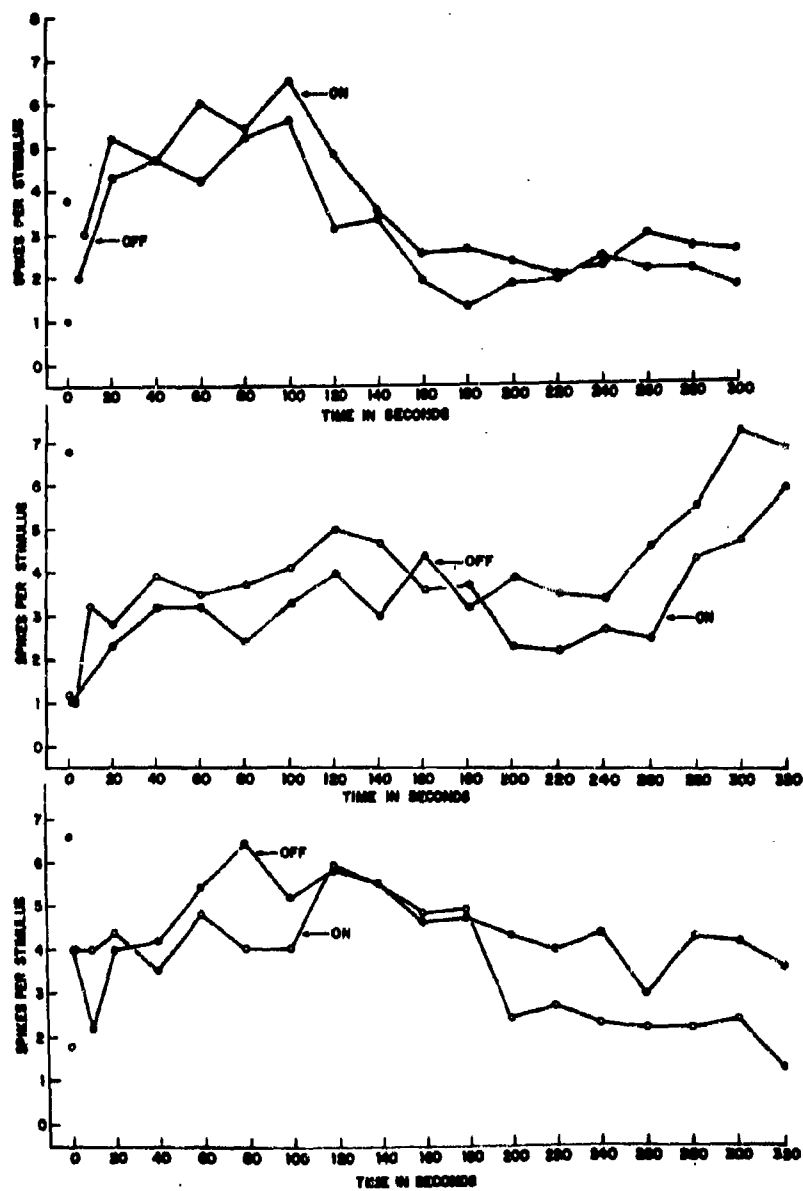
The recovery time of the ON cell to the light flashes. The intensity of the visual stimulus was at maximum, then reduced log -1.0, -2.0, and -3.0. Data were taken for this cell in 0.5 log unit steps to log -4.0, but these are representative data.



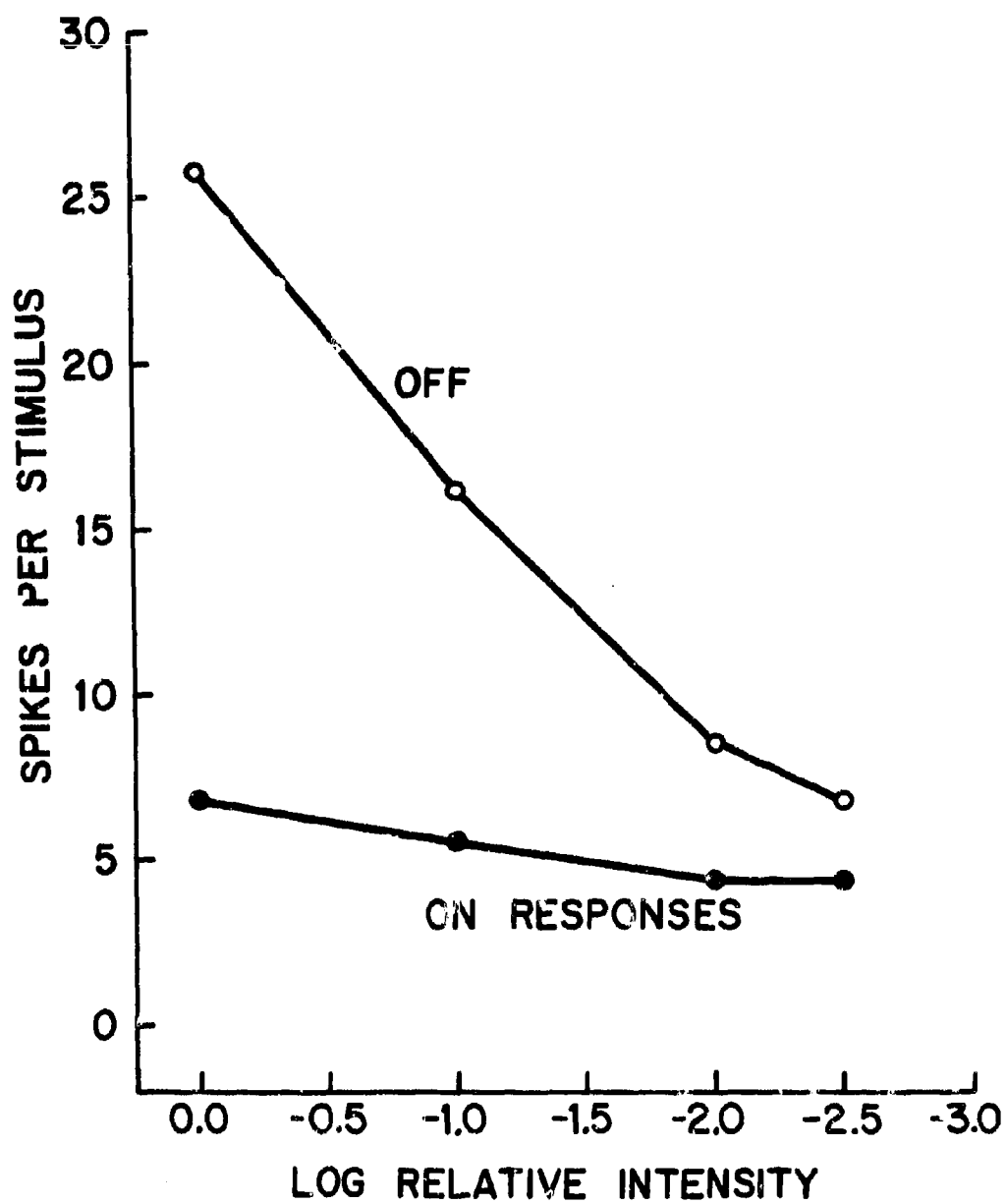
5. The spike response of an OFF cell for different stimulus intensities.



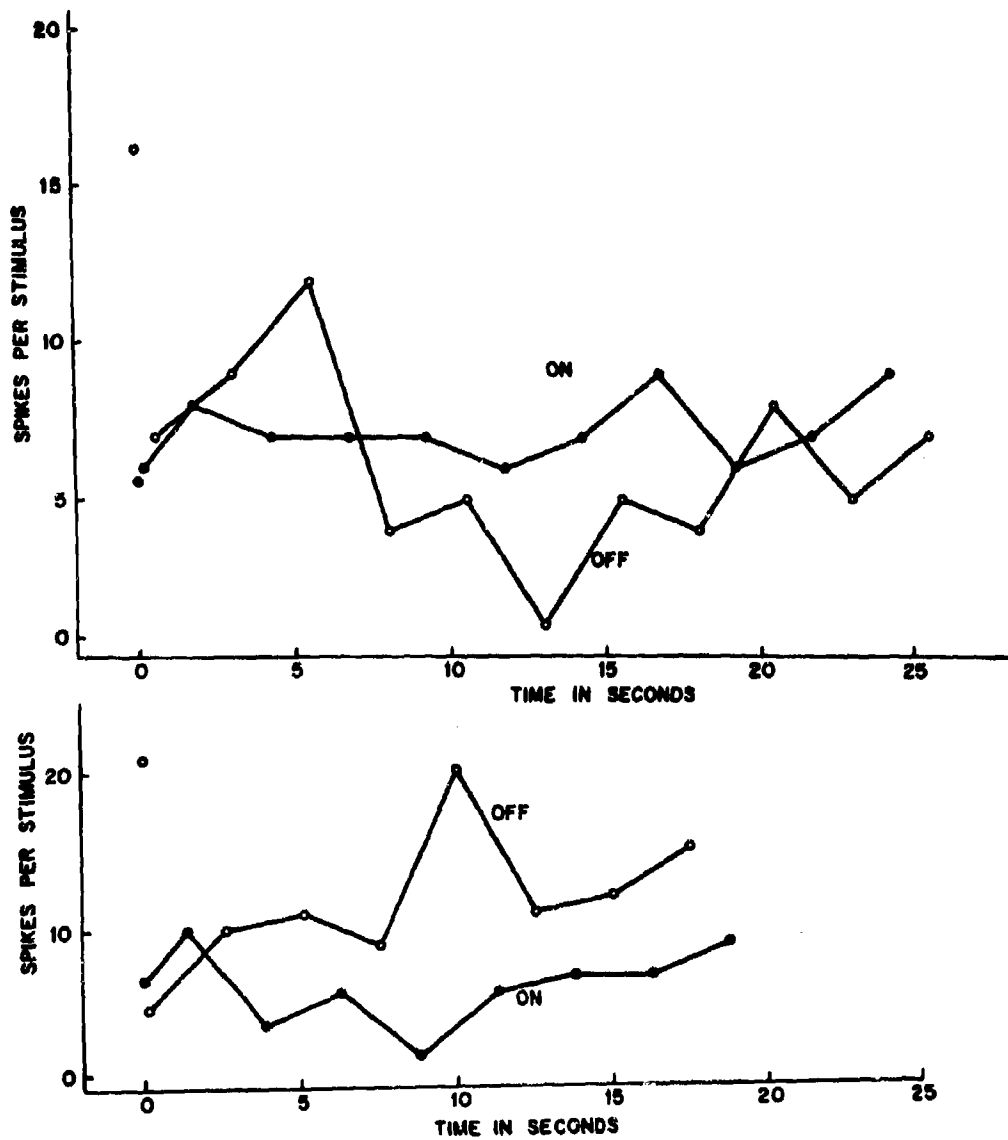
6. Responses of the OFF cell to flash No. 1, lower; flash No. 2, middle; and flash No. 3, upper.



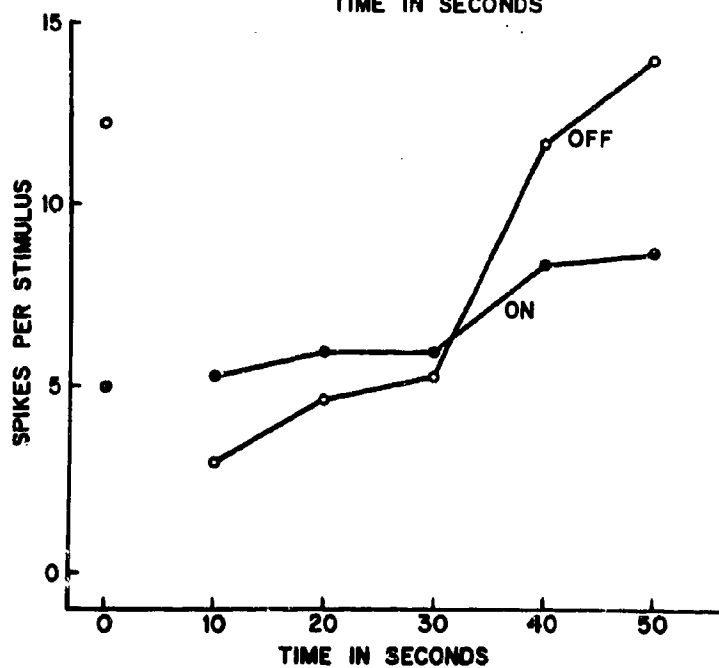
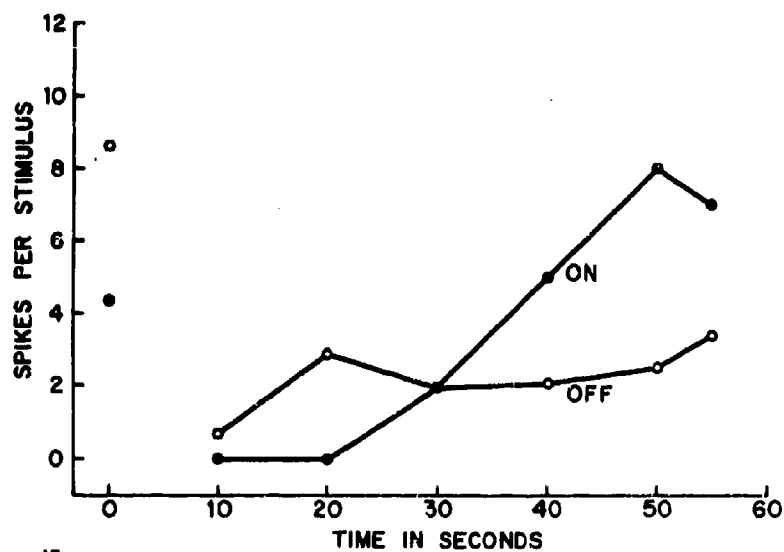
7. Responses of OFF cell of Fig. 6 to log -0.5, -1.0, and -1.5 relative stimulus intensity flash No. 1 are shown in lower, middle, and upper, respectively.



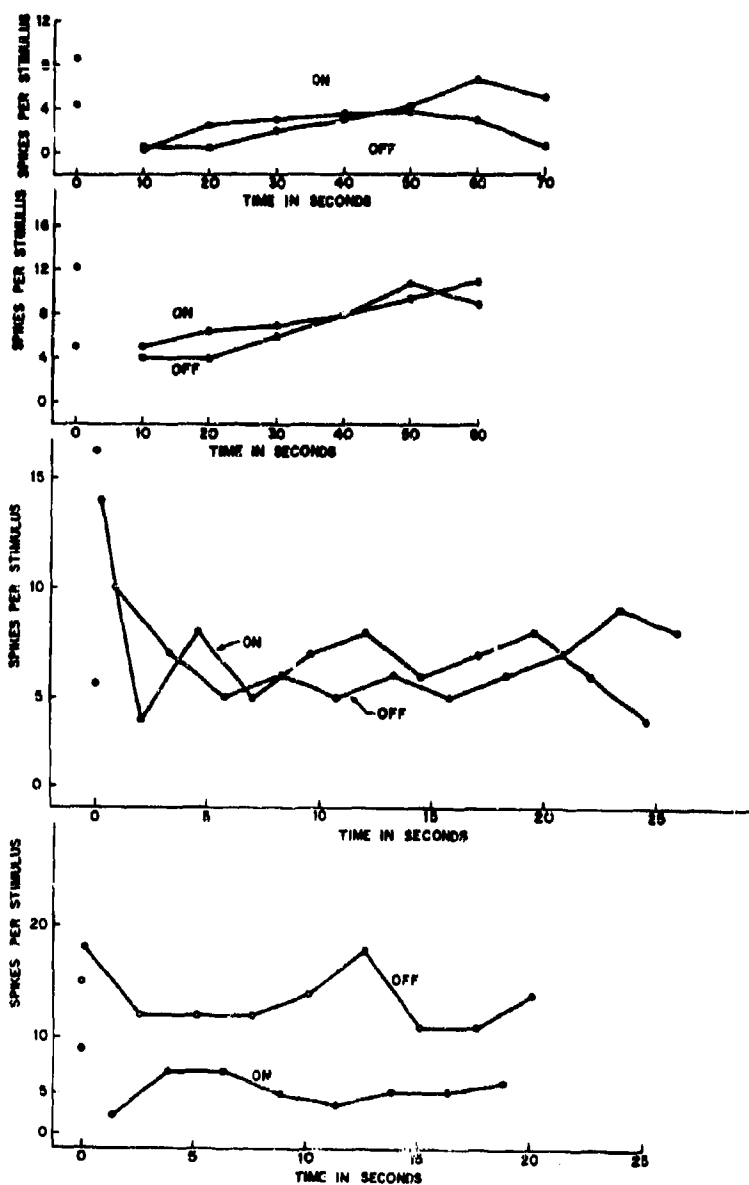
8. The ON-OFF spike responses for different visual stimulus intensities.



9. The recovery of the ON-OFF cell to flash No. 1 for relative stimulus intensity of log 0.0, lower curve, and log -1.0, upper curve.



10. The recovery of the ON-OFF cell to flash No. 1 for relative visual stimulus intensity $\log -1.5$, lower curve, and $\log -2.0$, upper curve.



11. The ON-OFF spike responses for flash No. 2. In this graph the log relative visual stimulus intensities are log 0.0, log -1.0, log -1.5, and log -2.0, from bottom to top, respectively.

LOCAL PHOTOPIC AND SCOTOPIC RESPONSES OF THE HUMAN RETINA

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Whenever the eye is exposed to a brief burst of light having an intensity which is sufficient to produce a temporary loss of sensitivity, a condition known as flash blindness ensues. Flash blindness may be regarded as a particular example of light adaptation. In general, light adaptation is produced by a stimulus of limited visual angle which is imaged upon the retina. Measures of the recovery of visual sensitivity are often made in the same retinal areas upon which the adaptation stimulus is imaged. In flash blindness, however, interest may center upon the recovery of retinal areas on which the adaptation stimulus was not imaged.

The physiological effects of flash blindness are not simple. Both photochemical and neural factors must be considered and these two may not be equally involved at different sites on the retina. Furthermore, the effects upon photopic and scotopic mechanisms must be distinguished. Nevertheless, some progress is being made in understanding retinal function. Several studies assessing the retinal effects of flash blindness have used the electroretinogram as a physiological index of visual sensitivity. One approach has been to determine the course of retinal recovery for a wide range of exposure conditions¹. Conventional recording procedures which involve the action of large retinal areas have been used. The aim of the present report is to call attention to recent developments which make it possible to study the electrical activity produced by restricted retinal areas. In the past the sensitivity of the electroretinogram to stimulation by stray light scattered beyond the image region to all parts of the retina has prevented successful study of local responses, but with the evolution of improved procedures, it is becoming increasingly feasible to investigate local retinal areas of

moderately small size. These improvements can be of value in studying many problems including those of flash blindness. This report will first review some of the steps that have led to these developments and will then describe some of the author's current research with localized responses.

The difficulty of obtaining localized response was shown in the work of Asher² and Boynton and Riggs³ whose investigations demonstrated that electroretinograms could be obtained to stimuli imaged on the blind spot. In fact, response was found to be practically independent of the retinal locus of the stimulus image. The retina appeared to be stimulated as a whole by stray light resulting from various imperfections in the optics of the eye, and the response which was generated by this stray light completely overrode that of the actual image. In some cases, however, an effect of stimulus position could be discerned. For example, Monnier and Boehm⁴ obtained data in which there was an interaction between stimulus position and the locus of the recording reference electrode.

Crampton and Armington⁵, working with the photopic components of the ERG, found evidence for localized activity using conventional recording procedures, except that the stimuli were of relatively low intensity. Figure 1 is an example of some of their data. The lower line describes the sensitivity of relatively large (50 μ V) photopic responses as a function of the position on the retina. Such responses result from relatively strong stimuli whose stray component is strong enough to stimulate areas lying beyond the intended image area. Because the response produced by this scattered light was much greater than that produced by the light within the stimulus area, no effect

of the position of the stimuli on the retina can be discerned. When sensitivity of 25 μ V responses is considered, however, the result is not quite the same. These responses, elicited by weaker stimuli, show a slightly higher sensitivity to central as compared with peripheral stimulation. Since the cone receptors have a higher density in the center of the visual field, these data gave some sign of localized photopic response. Although the indication is a marginal one and although the major part of the response is clearly still influenced by stray stimulation of non-focal areas, the data suggest that increasing success is to be had by applying weaker stimuli. But there is a limit. When stimulus intensity is reduced, response amplitude drops off and soon falls below the threshold of conventional recording methods.

Because of the recent rapid development of computer technology, it has now become possible to average many responses together and thus, to detect signals too small for resolution with conventional procedures. Dimmer stimuli can be used, and when they are directed to different retinal locations, the relatively small effect seen in Figure 1 becomes considerably more pronounced⁶, as can be seen in Figure 2. A much larger response was obtained in this example when stimuli of orange light were centered upon the fovea than when they were imaged on peripheral areas.

If an adaptation stimulus fills the retinal regions which are not of interest, their sensitivity to stray light will be diminished. Thus, under some conditions light adaptation may assist in obtaining localized responses. However, with this technique, responses become still smaller and computers become even more essential. Brindley

and Westheimer⁷, and Aiba, Alpern and Maasseidvaag⁸ have conducted experiments in which the luminance of an adaptation field surrounding the test area was carefully balanced against that of the stimulus. Stray light response was virtually eliminated, but it was still possible to observe local activity within the test area. The method was so successful that no response was seen when the stimulus was imaged upon retinal areas with no receptors such as the blind spot.

Another development has appeared in the experiments of Riggs, Johnson and Schick⁹. Their experiments, designed to investigate photopic visual mechanisms and color vision, made use of striped stimulus patterns which jumped back and forth within a circular field. There is every indication that this technique of stimulus alternation provides excellent control of stray light.

Two experiments are briefly summarized in the remainder of this report. They provide a further test of the method of stimulus - alternation. The object of the first experiment¹⁰ was to determine the relations among stimulus area, amplitude of response, and the number of receptors lying within the image area. The data provide evidence that the method is a good one for pinpointing local retinal activity. The stimulus alternation method has been used exclusively for recording photopic response. The second experiment shows that under suitable stimulus conditions it may also be used to produce scotopic response.

Apparatus and Method

The stimulator for these experiments was an optical apparatus which presented the subject with a grating pattern like that shown in Figure 3 in Maxwellian view. It appeared as a black and white

grid in which adjacent bars were switched off and on alternately. This was accomplished by shifting the grating back and forth with an abrupt square wave motion having a complete period of 0.5 sec. The widths of the dark and bright stripes are equal and the excursion of their movement was adjusted so that the area occupied by white stripes during one half of the period was exactly occupied by dark stripes during the other half of the period. This abrupt interchange of the bright and dark stripes produced retinal responses from within the stimulus field but not from beyond it. Since the flux entering the eye was constant and since there was no change or fluctuation in the stray light falling on retinal regions lying beyond the circular stimulus field, there was no stimulus for producing stray light responses. The diameter of the stimulus field, the visual angle subtended by the stripes, and the luminance level of the stimulus are all under the control of the experimenter. A steady fixation point was used to control the position of the stimulus on the retina.

The electroretinogram was obtained from a contact lens electrode with a reference to the cheek. After amplification with conventional equipment, the responses were processed by an average response computer triggered by the same mechanism which shifted the stimulus back and forth. Thus, the computer averaged the local responses which were produced by the stimulus alternation. Its output was the average response waveform with an upward deflection indicating positivity of the corneal electrode.

The first experiment was designed to show that the response produced by this method is directly related to the number of receptors lying in the image area. The procedure was that of an area-luminance

study. Stimuli covering a range of diameters from 2-12° and having a wide range of luminances were used. The largest responses were obtained by stimuli of high intensity and large area as may be seen by examining the sample recordings in the upper left-hand corner of Figure 4. In fact, these two variables were interchangeable over some of the range tested since responses of intermediate size could be produced either by the middle areas and strong luminances or the middle luminances and large areas. For more detailed analysis, the amplitudes of the positive or X-wave component were measured using conventional procedures, and graphs were constructed relating these measures to stimulus luminance for each of the diameters used. An example of the luminance relations for a 12° field is shown in Figure 5. The amplitude of the response increases regularly with luminance over much of the range, but as higher luminances are approached, response amplitude levels off achieving its maximum at a density value of about 2. Only data for the largest field are shown in this figure. For smaller areas the same form of luminance curve was seen, but, of course, for any luminance value, the size of the response was less for a smaller area than for a large. The plots for all areas tended to reach their maximum at the same luminance value. For any fixed luminance the response amplitude was positively related to stimulus area. These properties of the luminance curves suggested that it is reasonable to make a comparison between the number of cone receptors lying within the stimulus area and the response amplitude. This has been done in Figure 6, and an almost linear relation has been obtained. Earlier studies of the area luminance relation using conventional methods have failed to achieve

a direct relation to the number of receptors in the image area. Thus, the near linearity of Figure 6 provides a new demonstration that stimulus alternation does greatly reduce the effectiveness of stray light.

One of the advantages of stimulus alternation is that it permits a clear isolation of photopic activity, an advantage which is of particular usefulness in the investigation of color processes¹¹. However, experiments which are still in progress demonstrate that under appropriate conditions it may also be used to investigate local scotopic responses. This is done by allowing the eye to become completely dark-adapted before recording is initiated, by using stimuli of low luminance and by using stimuli with coarse grating spacings. These experiments have employed both red and blue stimulation in order to obtain data in which photopic and scotopic components are differentially involved. The sensitivities of central and peripheral positions of the retina have been compared. It was postulated that blue stimuli of low luminance would be effective in stimulating scotopic responses and that the largest responses would be seen in the peripheral retinal positions where the scotopic system is most concentrated. At higher luminance levels photopic mechanisms should be favored. Large responses to these levels should then be seen both to red and blue stimuli, and the central region of the retina where the cones have their highest concentration should be relatively more sensitive than the peripheral regions. The results agreed with the hypothesis as is shown in Figure 7. Responses to bright red and bright blue stimuli (matched for photopic luminance) are seen to the right of the figure. These stimuli marked "high luminance" were

about 1.5 log units above the color threshold and were, therefore, ones which should emphasize photopic responses. In agreement with expectation these responses are nearly the same size regardless of color. They are larger in the central than in the peripheral positions. The stimuli were reduced two log units to obtain the data shown on the right hand of the figure. The blue stimulus was now well below the observer's color threshold and the red could barely be discerned when it was in a non-central position. The response to blue is somewhat larger in the peripheral positions than in the central areas, but for red the pattern is reversed. The blue response must be triggered by scotopic processes.

Luminance curves based on a number of experimental sessions permit a more accurate assessment of these effects. Two examples, one for a central and the other for a peripheral position, are given in Figure 8. For the central fixation condition, shown on the right, luminance curves for red and blue are nearly the same. Nevertheless, a small difference can be discerned. The red curve lies slightly below the blue curve at low luminances, crosses it at a value of about 2.4 and exceeds the blue at higher luminances. For the nasal position, shown to the left, these differences are magnified - particularly at low luminances. The blue data lie well above those for red at the lower end of the curve but cross once more and are slightly below the red at high luminances. These data indicate that a beginning is being made in defining the conditions which are appropriate for scotopic as well as for photopic electroretinal perimetry.

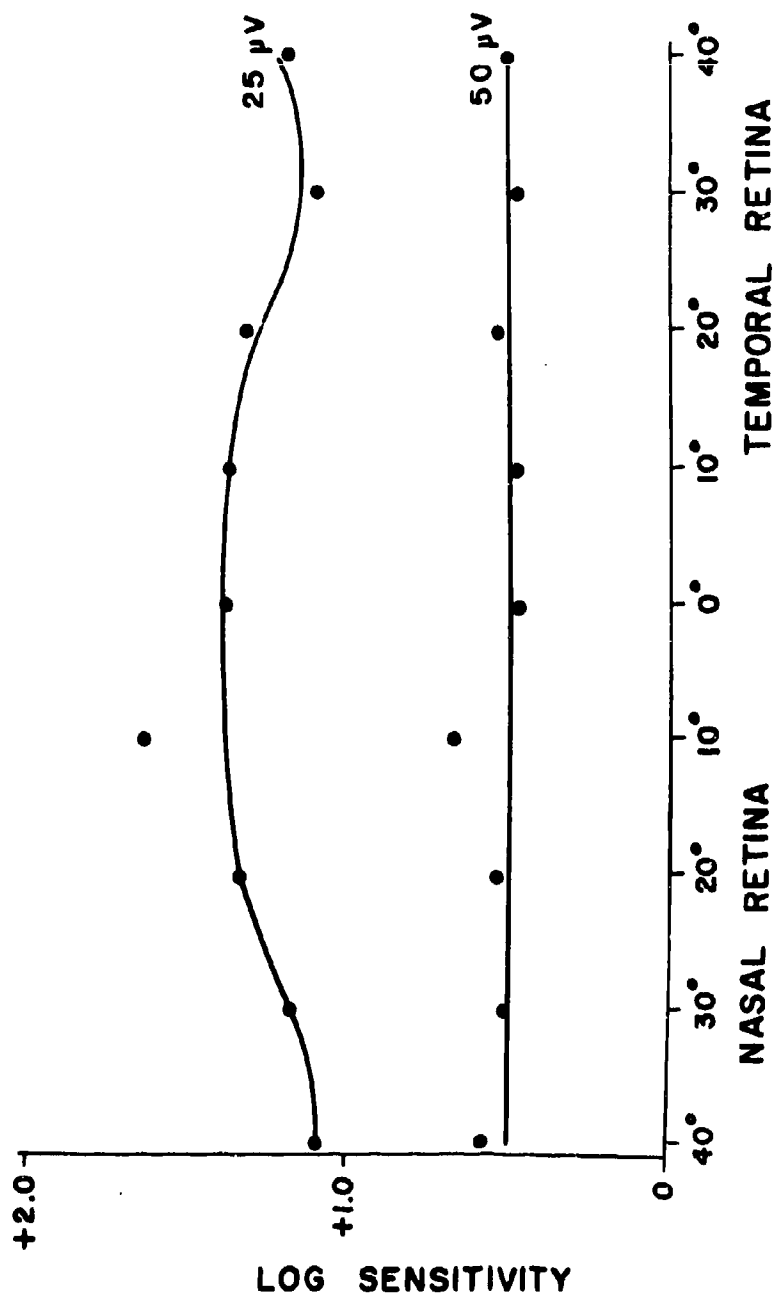
The research reviewed in this paper was conducted with the general goal of developing improved methods of detecting local retinal

responses in the intact human retina. These methods which are still in the process of development, should have both a basic and an applied value. They should contribute to a better understanding of basic visual function as well as to provide an improved clinical tool for evaluating visual defects. Perhaps they will also provide us with improved means for investigating the effects of flash stimulation and strong light adaptation.

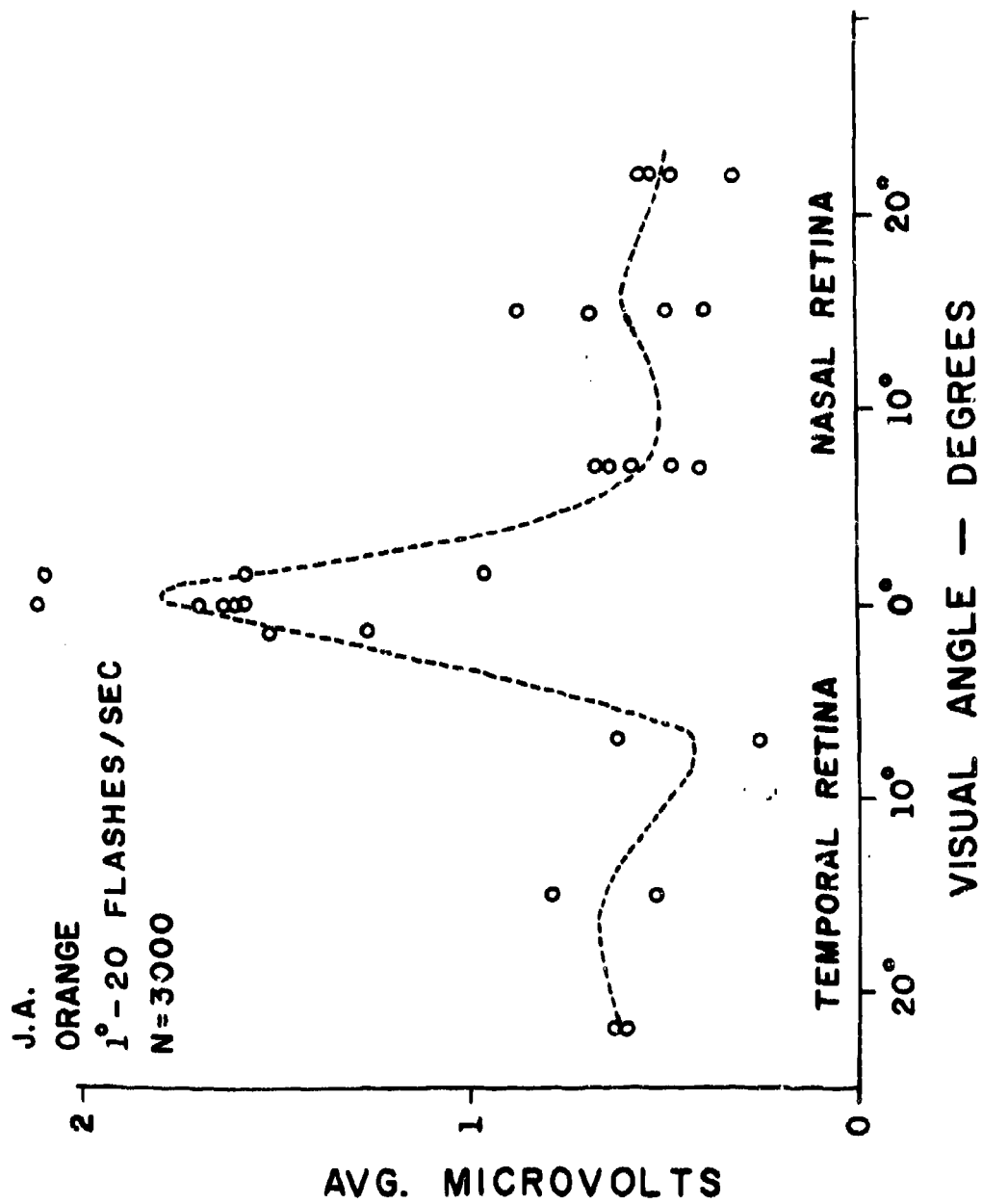
One drawback of computerized methods for obtaining localized responses is that a large number of responses must be averaged together in order to obtain responses from the smallest stimulus fields. Experimental sessions are necessarily prolonged. It may be possible to effect some reduction in recording time as more experience has been gained. There are undoubtedly optimum flicker rates and other stimulus conditions for obtaining the maximum amount of information in a limited amount of time. Advances in recording procedures may reduce the noise background against which responses are recorded, and thus may reduce the numbers of responses which must be averaged. As recording methods become more routine, they will certainly become more efficient. Thus, there is every indication that the electroretinogram will be of increasing value in future investigation of retinal phenomena.

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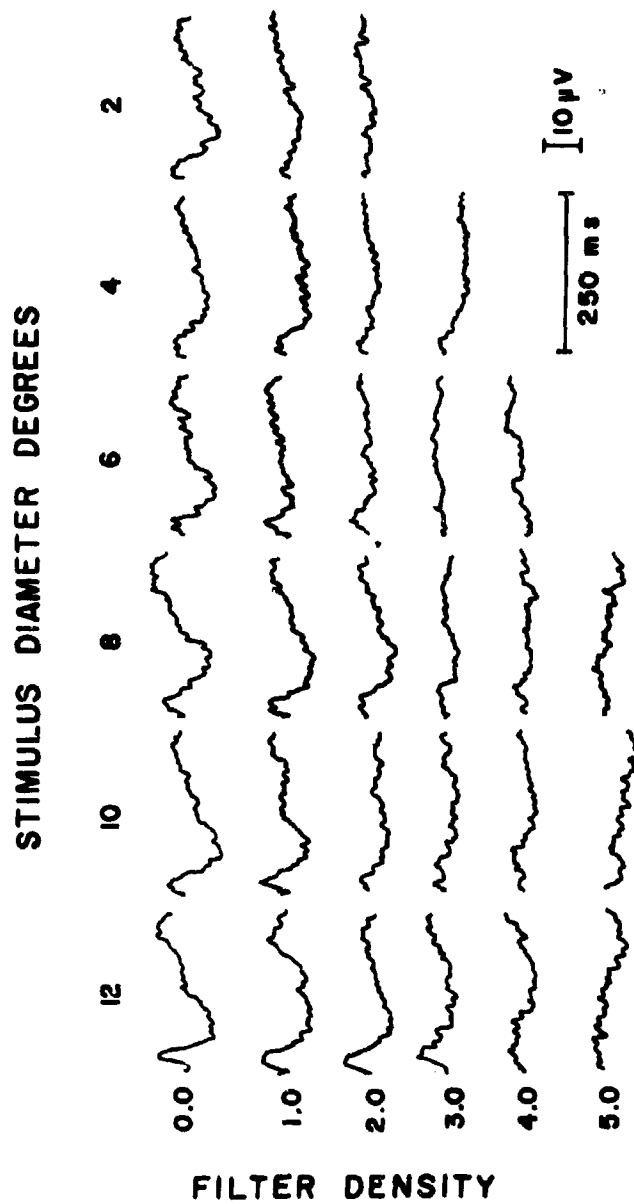
1. Log sensitivity of the retina for foveal and peripheral areas.



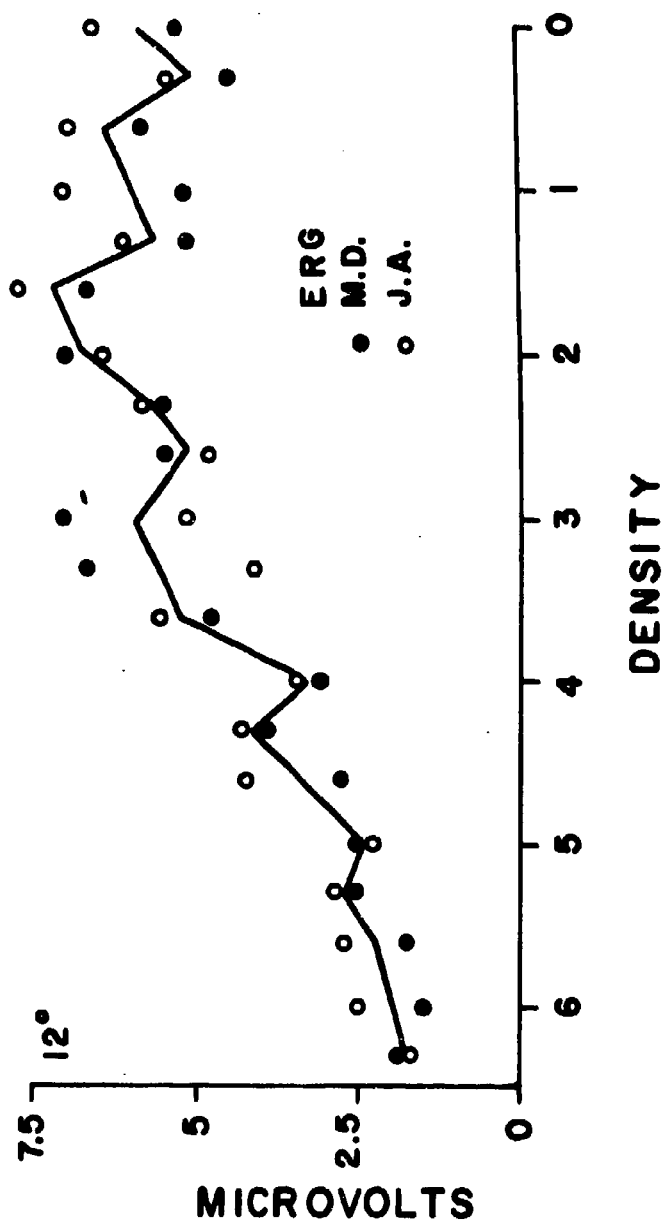
- Local responses obtained from the presentation of orange stimuli to foveal and peripheral areas of the retina.



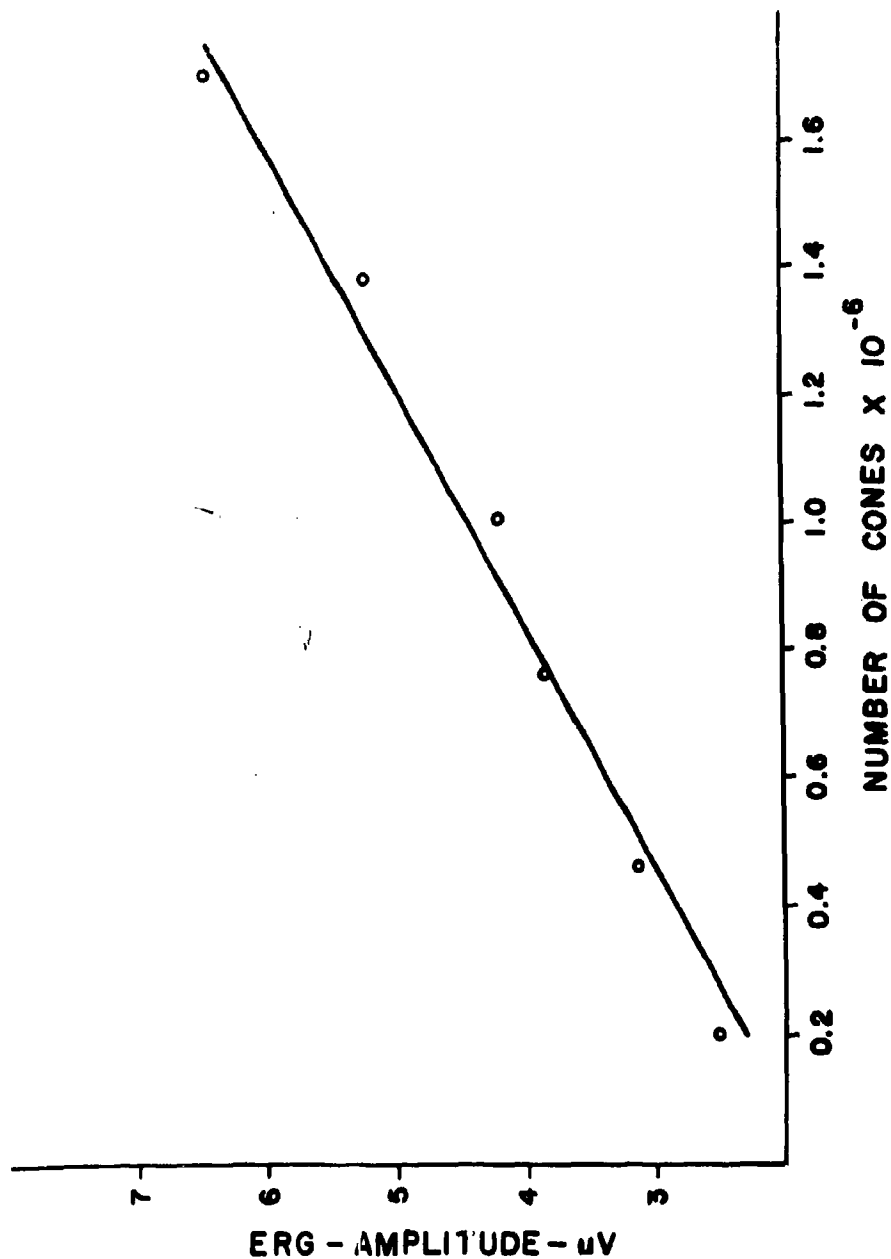
3. A Maxwellian view of the grating pattern presented to the subject by an optical stimulator apparatus.



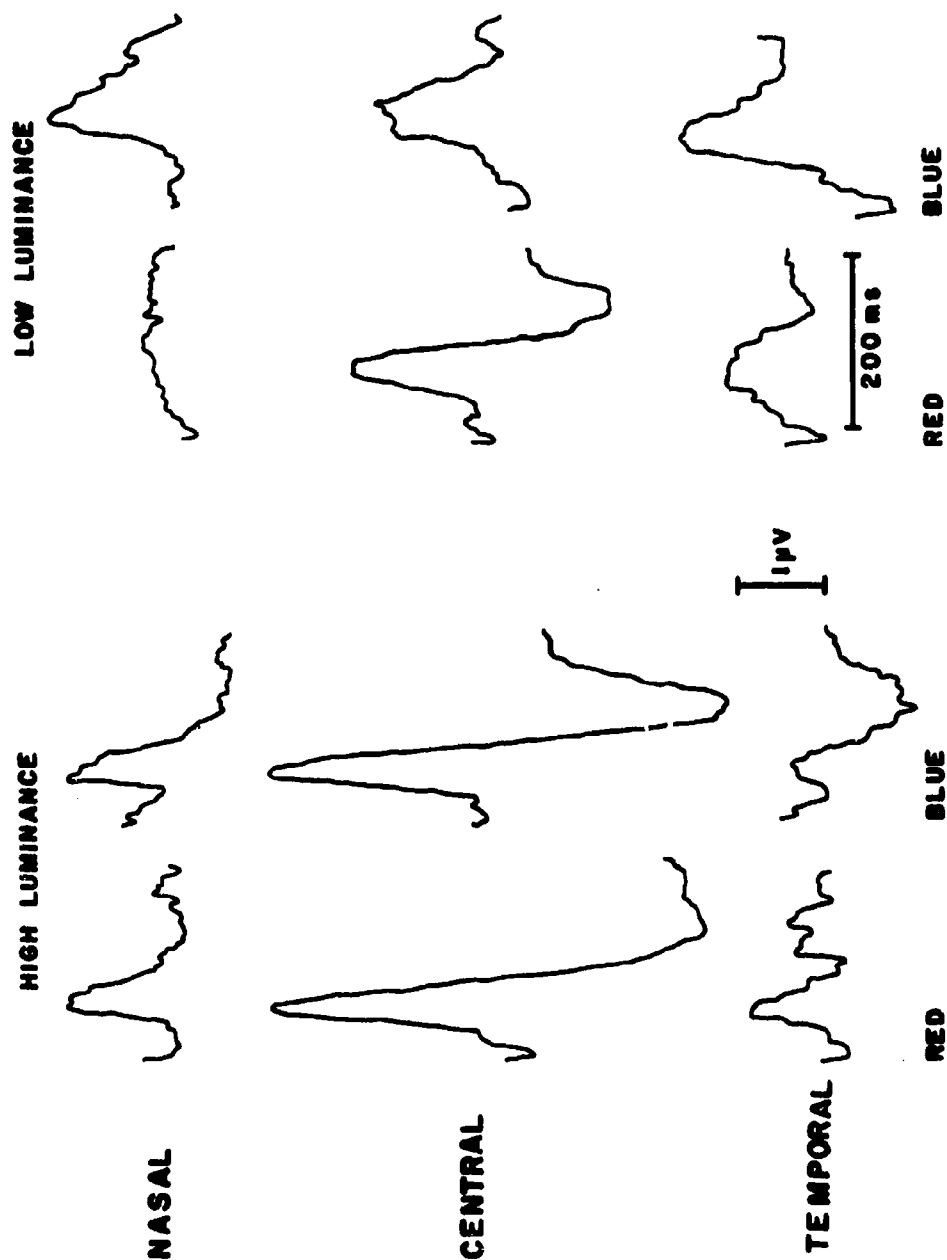
4. Sample recordings of retinal responses obtained by the presentation of stimuli covering a range of diameters from 2-12° and having a wide range of luminances.



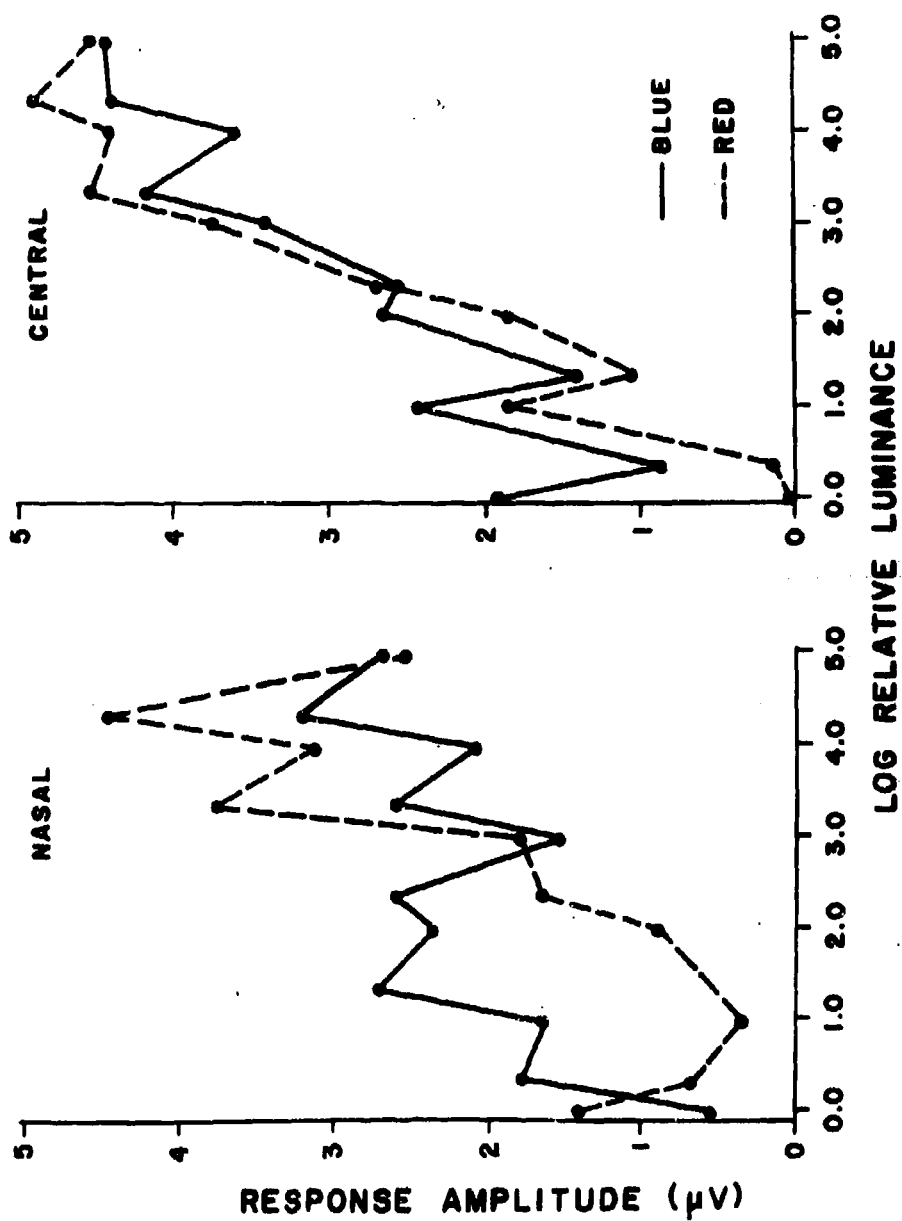
5. Retinal responses for 12° diameter stimulus presented through a wide range of luminances.



6. A comparison between the number of cone receptors lying within the stimulus area and the response amplitude.



7. Sample recordings of retinal responses to red and blue stimuli presented to foveal and peripheral areas at "high" and "low" luminances.



8. Responses obtained from nasal and central areas of the retina showing the effects of the presentation of red and blue stimuli at a wide range of luminances.

FLASH BLINDNESS EXPERIMENTS WITH ANIMALS:
ELECTRORETINOGRAPHIC AND BEHAVIORAL STUDIES*

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This paper is an attempt to relate the electrophysiology of the retina with the performance of a behaving animal. The electrophysiological response we have studied most is the electroretinogram (ERG) and I would like to begin with a brief review of the components of the time varying potential recorded when the eye is stimulated by a flash of light.

The upper curve in Fig. 1 is a component analysis of the electroretinogram as broken down by Granit¹ as early as 1933. He found at least three components to the response. One of these was negative, (P III) starting with the stimulus onset, staying at the same level of negativity until stimulus offset. Until recently there was some question if the component P III did in fact exist. We now know that it does exist and appears to arise somewhere in the inner plexiform layer of the retina. This is the retinal area where the photoreceptor cells synapse with the next layer in the retina, the bipolar cells. The component which Granit called P II is the major part of what we now call the B wave, and probably originates in the bipolar cell layer according to the work of Dowling², and Noell³.

The analysis presented in the lower part of Fig. 1 was reported by Auerbach and Burian⁴ 22 years later. They used intense flashes of white light and recorded the electroretinogram from the human eye. Through some clever experimentation with light adaptation, they detected multiple components in the human ERG. The typical response after light adaptation is shown as a solid line in the figure. It is made up of an a wave and an x wave and a b wave. Their work

* This research program was supported by the U. S. Army Medical Research and Development Command, Experimental Surgery Branch, under contracts Nos. DADA-17-67-C-0019 and DA-49-193-MD-2457.

indicated that this complex response was made up of a negative going potential and a positive going potential followed shortly by another negative going potential and a second positive going potential. These are designated A^1 prime, X prime, A^2 prime and B prime. This analysis is an adaptation of Fig. 12 of Auerbach and Burian who did not show any ordinal or abscissal values. The time scale is consistent with their stimulus which was a xenon arc flash of 15 microsec duration.

One way of comparing ERG's is to examine spectral sensitivity curves such as those shown in Fig. 2. These spectral sensitivity functions have been generated from measurements made on the x wave and b wave of the ERG of the mangabey. The procedure by which these curves are constructed has been discussed by Armington and Biersdorf⁵. Briefly, responses are studied for a long intensity range at each wavelength selected and response amplitude is plotted as a function of intensity. A family of curves, one for each wavelength, is generated and a criterion amplitude that passes through a linear portion of each is chosen. A perpendicular is dropped to the abscissa from the point of intersection and the intensity required to elicit the criterion amplitude or criterion implicit time is determined for all wavelengths. Sensitivity functions constructed from the implicit time or magnitude of the b wave fairly well describe the scotopic luminosity function. The implicit time and magnitude functions are different when measured from the x wave. The shape of the implicit time function from the x wave is shown in Fig. 2 and is of interest because it correlates very well with some of the behavioral data obtained.

We can also record ERG responses evoked by flickering light. We stimulate the eye with pulses of light and pulses of dark, a square wave light pulse. If you use a flickering stimulus at low frequencies, the response appears to be primarily mediated by scotopic mechanisms in the retina and we attribute this to the retinal rods. If you

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increase the flicker rate to something over 15 cycles per second, the response that you get with a mixed primate retina appears to be related to photopic events which we attribute to cones. This has been demonstrated by a number of people (Dodt⁶, and Heck⁷, among others).

In the course of a study investigating the effects of laser exposures of large retinal areas, we exposed two Macaque monkeys to a ruby laser pulse at a retinal energy density of 0.18 J/cm^2 which is about one-fourth the threshold for visual damage. We did a flicker electroretinogram prior to laser exposure. Six days later we brought the animals back and did the same experiment over again. Jones and McCartney⁸ had indicated that the main damaging effect of laser exposure will be evident at about 6 days. We then sacrificed them and sectioned the eyes. The data is presented in Fig. 3. The response to a 10 cycle per second flicker before laser exposure is described by the filled circles. It is a little narrow but something like a scotopic luminosity function. At 25 cycles per second before exposure we got the function indicated by the diamonds. This is quite close to the standard photopic observer curves. After the animals were laser exposed at $.18 \text{ joules/cm}^2$, we repeated the experiment. At 10 cycles per second we found that we did not get the same kind of function we had found before. In Fig. 3, this is shown by the open circles. We now had something which looked much more like a photopic curve at 10 cycles per second.

This led to an investigation where we began to use the laser as a bright light source to insult the retina, hopefully below the visible damage level, in order to study cone mechanisms. For this investigation we chose the Sooty mangabey primarily because of

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Polyak's⁹ statement that the mangabey has more cones than any other primate and that these cones are denser in the fovea. (In preliminary cell counts I have also found the rod-free area to be much larger than in the Macaque). Previous work with the mangabey ERG (Jones, et al.¹⁰) revealed that there are photopic and scotopic events which are isolated with reference to time. That is, the time between the x wave and the b wave is great enough that the x wave is nearly always back to baseline before the b wave begins. This means that we can see a well-defined x wave at all wavelengths and at nearly all intensities in the range in which we work. The wave form of the Mangabey ERG can be seen in Fig. 4. These records represent fifty averaged responses to a 100 msec stimulus with an inter stimulus interval of five seconds. This stimulus wavelength is indicated at the upper right of each inset and the log relative density at the lower right. The high frequency potentials seen on the x wave were first reported by Cobb and Morton¹¹. These components are called electroretinal oscillations or oscillatory potentials. The oscillatory potentials can be manipulated with spectral adaptation (Rendahl¹², Heck and Rendahl¹³). Using a continuous red light, or a ruby laser, the third oscillatory potential, which can be seen in Fig. 5, can be depressed or completely eliminated. This third "hump" appears to be associated with the red sensitive mechanism as has been demonstrated by Heck and Rendahl¹³ dealing with protanopic humans and with some deuteranopic and light-adapted normal humans.

With the Sooty mangabey, a ruby laser exposure of approximately 0.2 J/cm^2 on the retina over a large retinal area produces changes in the implicit times of the x and b waves as well as depression of the third oscillatory potential (Jones, Adams, and Bryan¹⁴), however,

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where the ruby laser at 6943A or continuous red light adaptation seems to affect only the third (and possibly the fourth) oscillatory potential, continuous adaptation with blue light eliminates all of the oscillatory potentials as well as depressing the b wave.

We attempted to use a pulsed argon laser to manipulate the oscillatory potentials with greenish-blue light. The argon laser we used has two lines, one in the green and one in the blue. The ERG stimulus spot was restricted to 2° and centered on the fovea with a surround of dim white light. A flash with a wavelength of 590 nm was presented with a 5 second inter stimulus interval and fifty consecutive responses were averaged. The ERG from this procedure is shown in Fig. 6 (time 0). The oscillatory potentials are still there but smaller. The retinal area involved is also small, about .1 of a square millimeter. The b wave seen is due to stray light. Three minutes after exposure with the argon laser at about .02 joules/cm², we found no visible oscillatory potentials. An interesting difference with the argon laser was that at 3 minutes post exposure, we see no change with reference to time like that found with ruby laser exposure, and magnitude of the b wave shows an increase of 22-1/2 percent. In this case, light adaptation seems to make the b wave larger rather than decreasing it. At 90 minutes post exposure there are still no oscillatory potentials but the amplitudes and latencies of the major components of the wave, A¹, x A², and b have returned to normal.

The behavioral portion of this program was started at Honeywell by Dr. H. G. Sperling about 5 years ago. The goals of this program were to investigate the effects of lights having the characteristics of laser radiation, and of narrow-band filtered atomic flash upon

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the spectral sensitivity of primate eyes. The approach was to determine spectral sensitivity of the retina under a neutral white-light condition and to add continuous wave or flash intensities of narrow-band radiation to this background light, and then redetermine the spectral sensitivity for each intensity level and at each adapting wavelength. Thus, changes in the spectral sensitivity function might be related to wavelengths, duration and intensity of exposure. The results are expressed in absolute radiometric terms and can serve as the basis for a generalized mathematical model of the effects of laser and other spectral line exposure on visual sensitivity.

A xenon arc lamp, focused through appropriate lenses, beam splitters and shutters supplied the test flash. A manually adjustable double monochromator regulated the wavelength of the test flash, and a variable filter disc (referred to in the text and figures as a wedge) was used to manually regulate the intensity. The wedge was calibrated in degrees so that a difference of 20 degrees equaled an intensity change of $1/4$ log unit. The optical system provided a 2-degree Maxwellian view of the test flash against a 20-degree adapting surround light, viewed through a telescope eyepiece. The adaptation field was 3000 Trolands at a color temperature of 2854°K.

Animal subjects were restrained in a commercial primate chair (Foringer No. 1206) enclosed in a double-shielded permanent test chamber. A solenoid liquid dispenser apparatus, a shutter, a white noise generator, and a hand bar were used in conjunction with Massey Dickenson and Tektronix control circuitry. The chair was so situated that subjects had easy access to both the telescope eyepiece and a mouthpiece connected to the solenoid liquid dispenser. The position

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of the mouthpiece determined the subject's eye alignment relative to the telescope eyepiece.

Subjects were deprived of water for 24 hours and trained to depress the bar at the onset of white noise and to release it within 622 msec after the onset of the monochromatic flash. The monochromatic flash, 100 msec in duration, occurred randomly (p of 0.5 after each 2-second interval after the bar was depressed). Each reinforcement consisted of 2 cm³ of reconstituted orange juice (Tang) delivered through the mouthpiece immediately following bar release. Any bar release occurring outside of the prescribed interval resulted in a 20-second "time-out" period.

The procedure is, basically, a modified method of limits adapted to an operant paradigm. The performance required of the subjects for the method of limits sensitivity trials was essentially the same as that described in the preliminary conditioning. The reinforcement schedule became intermittent, however. After a 5-minute adaptation period, the monochromator was set at the first of 22 wavelengths presented for threshold determination. A minimum of nine presentations established the subject's threshold at any given wavelength. The intensity of the stimulus flash at each presentation was varied manually by the experimenter. Beginning at an intensity value above threshold, the experimenter, upon each presentation of the stimulus, successively decreased the intensity in steps of $1/4$ log units (a wedge difference of 20 degrees) until reaching a value at which the subject received no reinforcement. On the next presentation, the experimenter increased the intensity by $1/4$ log unit. This placed the intensity at the last value where the subject received reinforcement. If the subject was again reinforced at this value, the

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experimenter repeated the above steps, this time decreasing the intensity by $1/8$ log unit (10 degrees difference on wedge) until the subject again failed to earn a reinforcement. Returning the wedge to the previous reinforcement intensity, the experimenter repeated the descending series, but in $1/16$ log unit steps (5 degrees difference on the wedge) until reaching an intensity at which the subject was not reinforced. This was the suspected threshold. The intensity remained at this value for the next presentation. If the subject failed for the second time to earn a reinforcement at this intensity, the value was recorded as the threshold.

The spectral sensitivity functions for two animals are presented in Figs. 7 and 8. Every spectral point is the mean of 225 data points, and the envelope indicates + or - one standard deviation from the mean curve. The abscissa is frequency in reciprocal centimeters with a wavelength scale at the top. The ordinate is log reciprocal mean quanta and represents the efficiency of the retina in terms of the number of quanta per flash. Qualitatively the data from the two animals is somewhat dissimilar, primarily because the humps and dips are more pronounced with M1. Statistically the experimental outcomes are not qualitatively or quantitatively different for these two animals. Humans have been tested in the same apparatus and the human data and the monkey data fall right on top of each other. In this system the monkey is a perfectly good surrogate for a man.

Fig. 9 is a study with Monkey 1 in which 100 Trolands of 650 nanometers spectral red was added to the white background. There is no significant effect on the animal's spectral sensitivity. The X_s are the general baseline plotted in Fig. 7. The baseline that's taken in conjunction with the experiment is designated by R1M1 and

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the spectral adaptation data is designated by RW1M1. The effect of adding 100 Trolands of spectral green to the white background can be seen in Fig. 10. Statistically there is no significant difference. However, an addition of 100 Trolands of spectral blue to 3000 Trolands white produces a large effect which can be seen in Fig. 11. The animal is depressed in overall sensitivity across the entire spectrum, and the blue lobe on the curve has been depressed about one order of magnitude in sensitivity.

Other studies have been done adding 10,000 Trolands of spectral light. In Fig. 12, the addition of 10,000 Trolands of red does in fact have a profound effect on the animal's spectral sensitivity across the entire spectrum. Sensitivity to the long wavelength region of the spectrum is severely depressed while the shapes of the green and blue functions are only slightly affected.

Fig. 13 presents the effects of 10,000 Trolands of spectral yellow. If you examine the adaptation data and consider where the retina is most sensitive under a condition of spectral adaptation, you find that the main peak of spectral sensitivity is at about 580 nanometers. Adaptation to 10,000 Trolands of yellow at 585 nm change the shape of the spectral sensitivity function very little. There is some relative depression of the red spectral peak but the primary effect is a decrease in sensitivity throughout the spectrum.

In the green region of the spectrum, seen in Fig. 14, addition of 10,000 Trolands of spectral green at 520 nm produces severe depression through the green region of the spectrum, relative depression across the entire spectrum and the least effect is shown in the blue. The addition of 10,000 Trolands of spectral blue produces a spectral sensitivity function that is depressed well over one order of

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magnitude, approaching two orders of magnitude. Its peak sensitivity is near 580 nm, and the residual function can be fitted by a Dartnall nomogram function¹⁵ for a pigment with its lambda max at about 577 nm.

CONCLUSIONS

The ERG is an interesting biopotential to study. It is a sort of epi-phenomenon in that it is recorded as a response to a light stimulus but appears to have little to do with vision directly. However, even if the ERG is a secondary phenomenon generated by and accompanying visual events, we can infer a great deal about the visual capabilities of an observer from correlative studies of his ERG and performance.

We have demonstrated that adaptation to red light produces characteristic changes in the ERG. The spectral sensitivity of an animal adapted to red light also shows characteristic changes. In both cases, the magnitude of the change in the dependent variable is directly related to the intensity of the adaptation light.

Laser induced changes in the ERG probably have a correlate in the visual performance and the answer may lie in finding the right visual test. There have been a number of demonstrations that sub "threshold" exposures do not irreversibly reduce visual acuity¹⁶. There have been almost no tests of the effects of sub "threshold" exposures on dark adaptation, anomaloscope matches, absolute threshold or color sensitivity. We are currently carrying out both physiological and behavioral studies of the effects of continuous and pulsed spectral sources on primate vision in an attempt to examine some of these functions.

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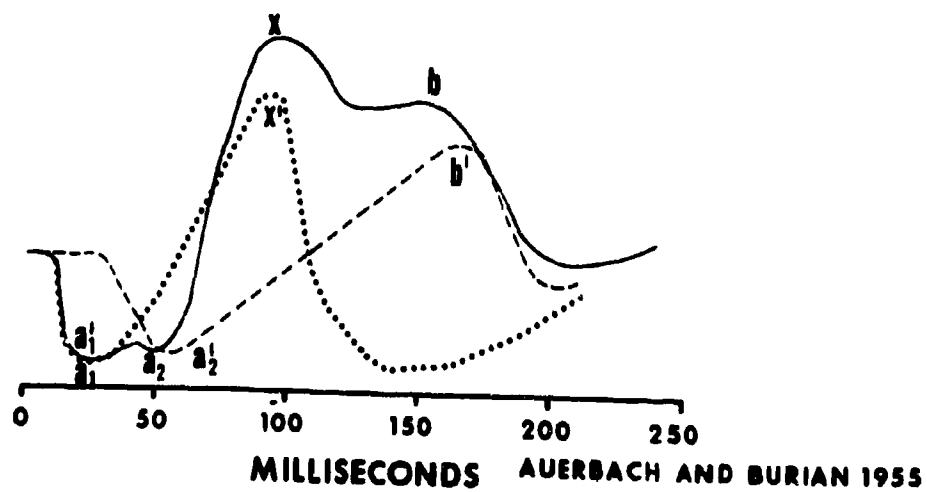
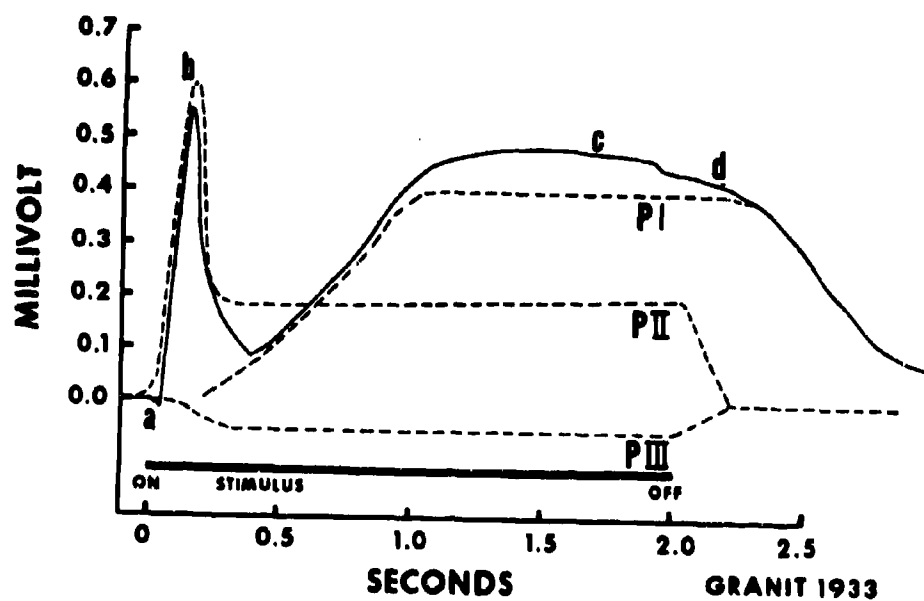


Fig. 1. Component analysis of the ERG by Granit (upper portion) and Auerbach and Burian (lower portion).

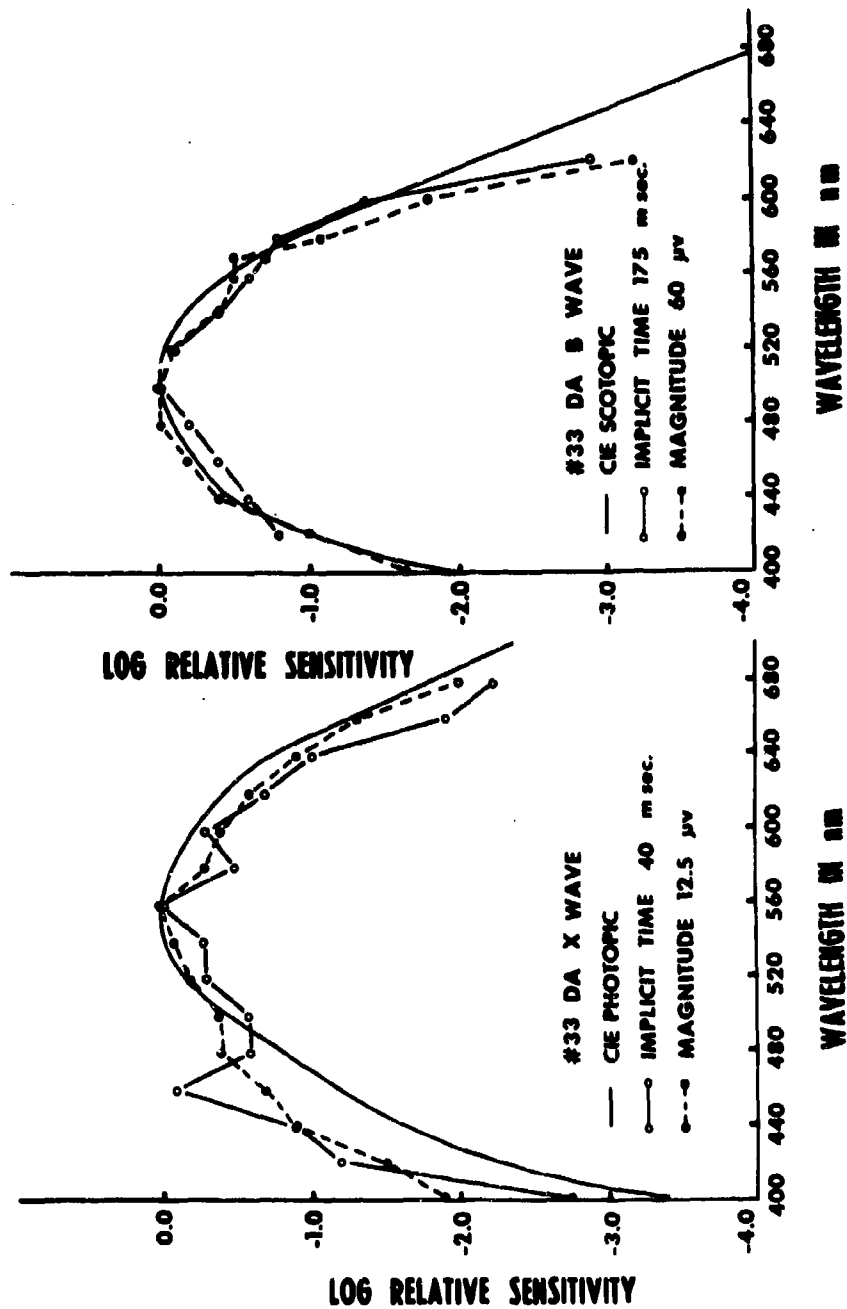


Fig. 2. The spectral sensitivity of the Sooty Mangabey as determined from the ERG amplitude and implicit time.

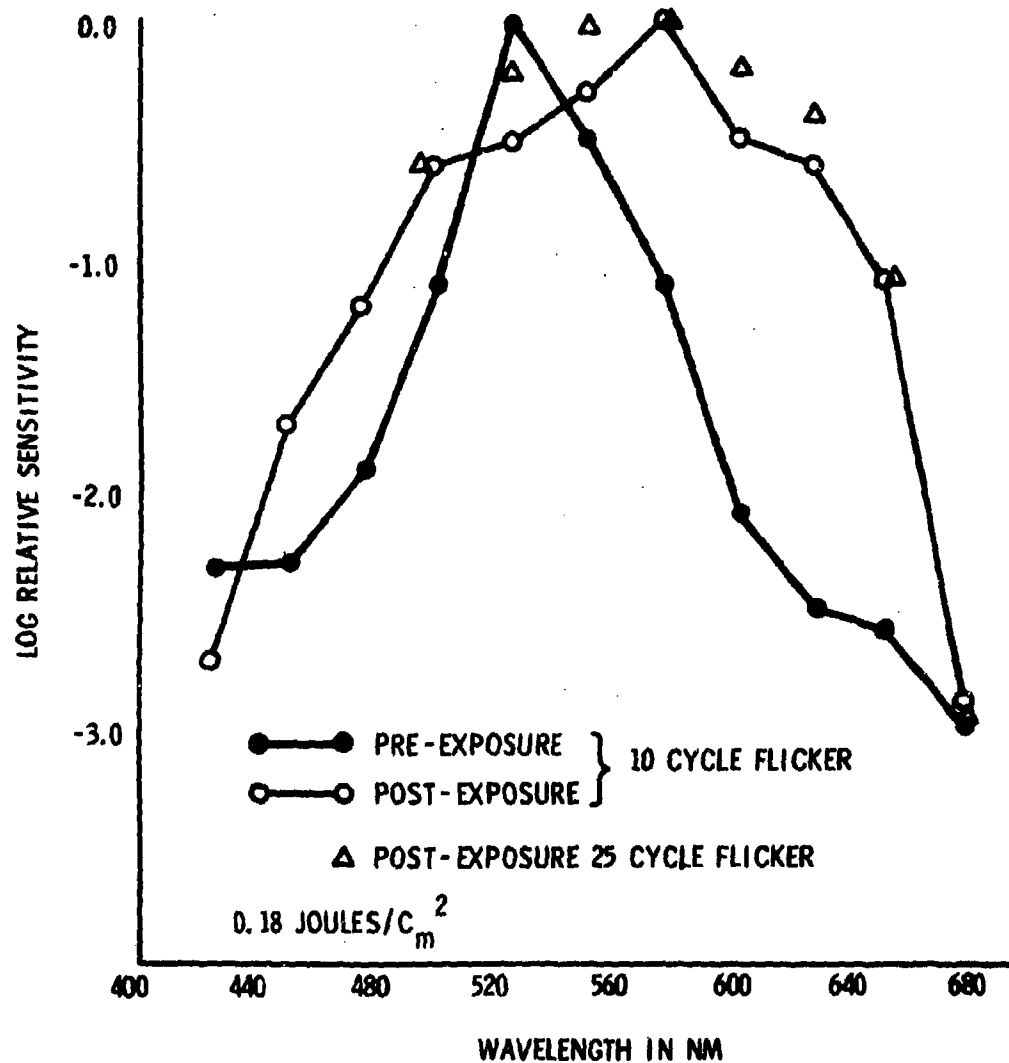


Fig. 3. The spectral sensitivity of Macaca Cynomolgus determined by flicker electroretinography pre and post-laser exposure.

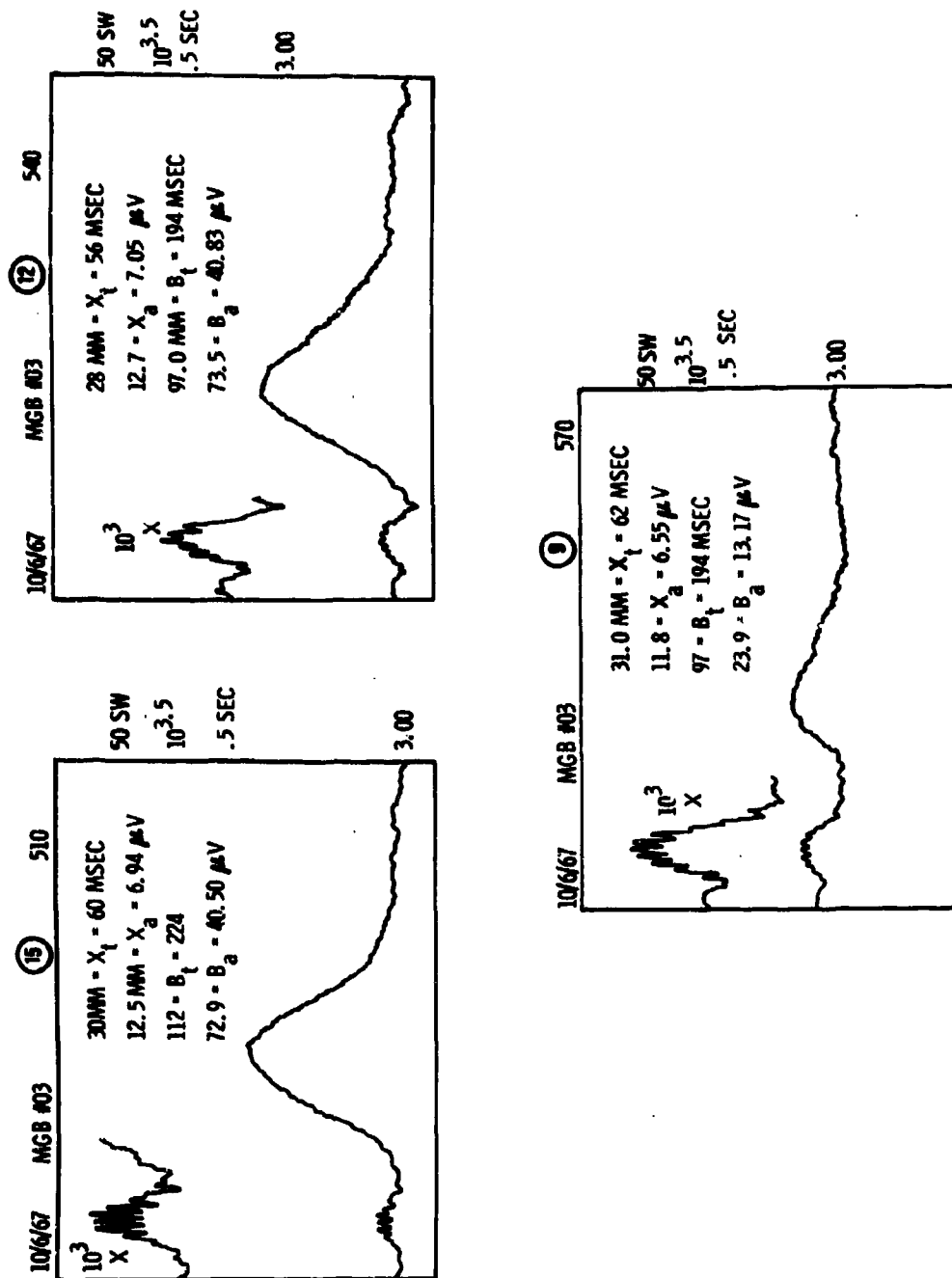


Fig. 4. Typical mangabey ERG as a function of wavelength.

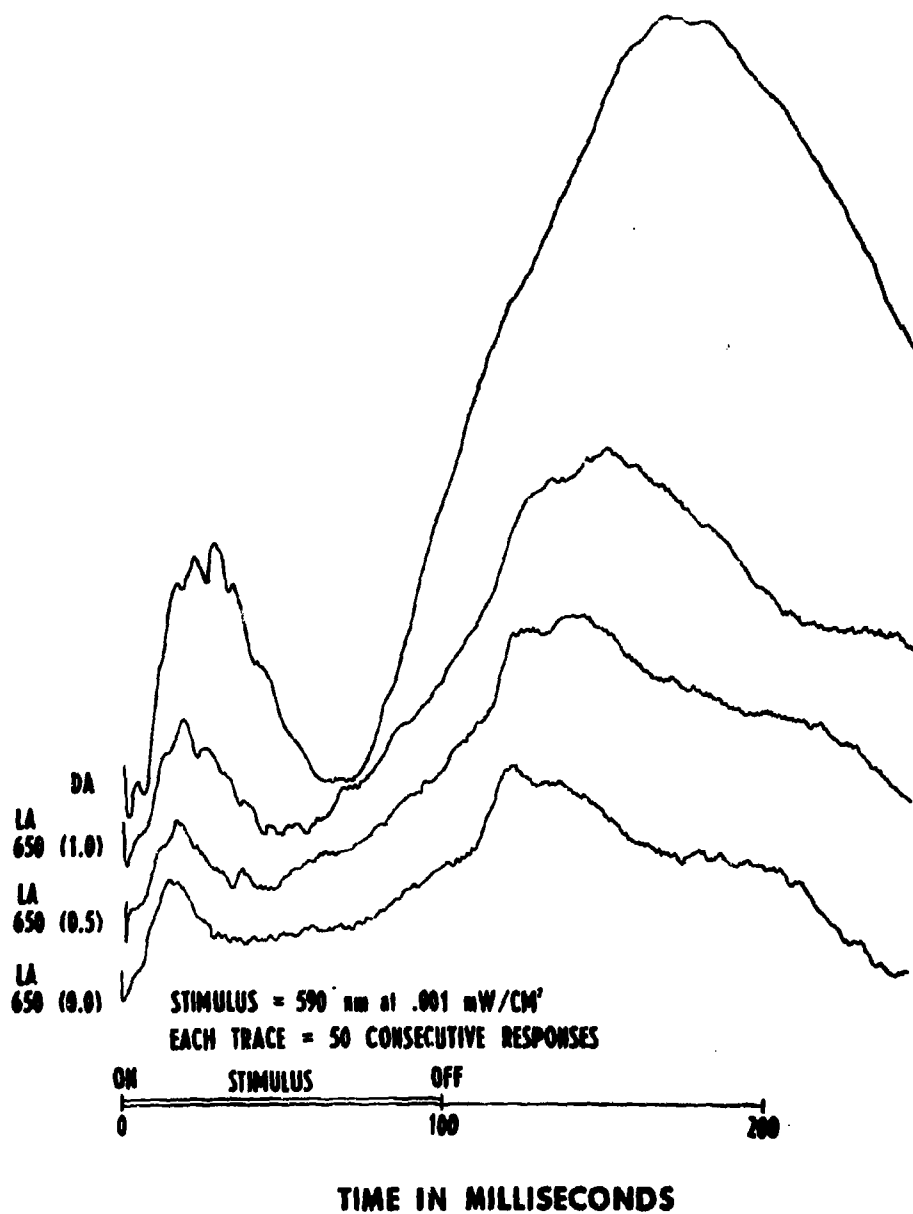


Fig. 5. Suppression of the third oscillatory potential and b wave by adaptation to continuous red light. The adaptation condition is listed at the left of each response.

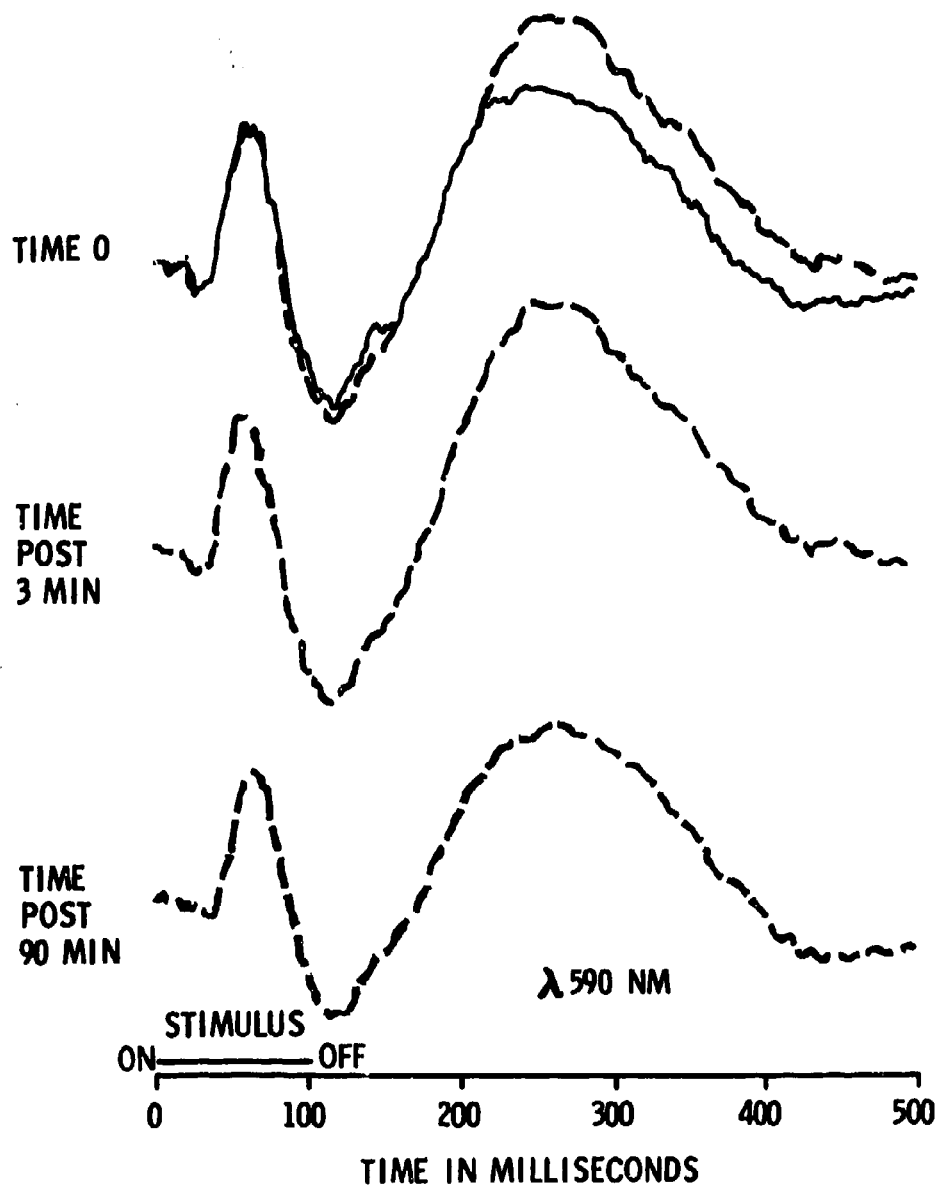


Fig. 6. The effects of pulsed argon laser exposure on the ERG. The upper figure shows the pre-exposure wave form (solid line) and the 90 sec post exposure wave form (dashed line).

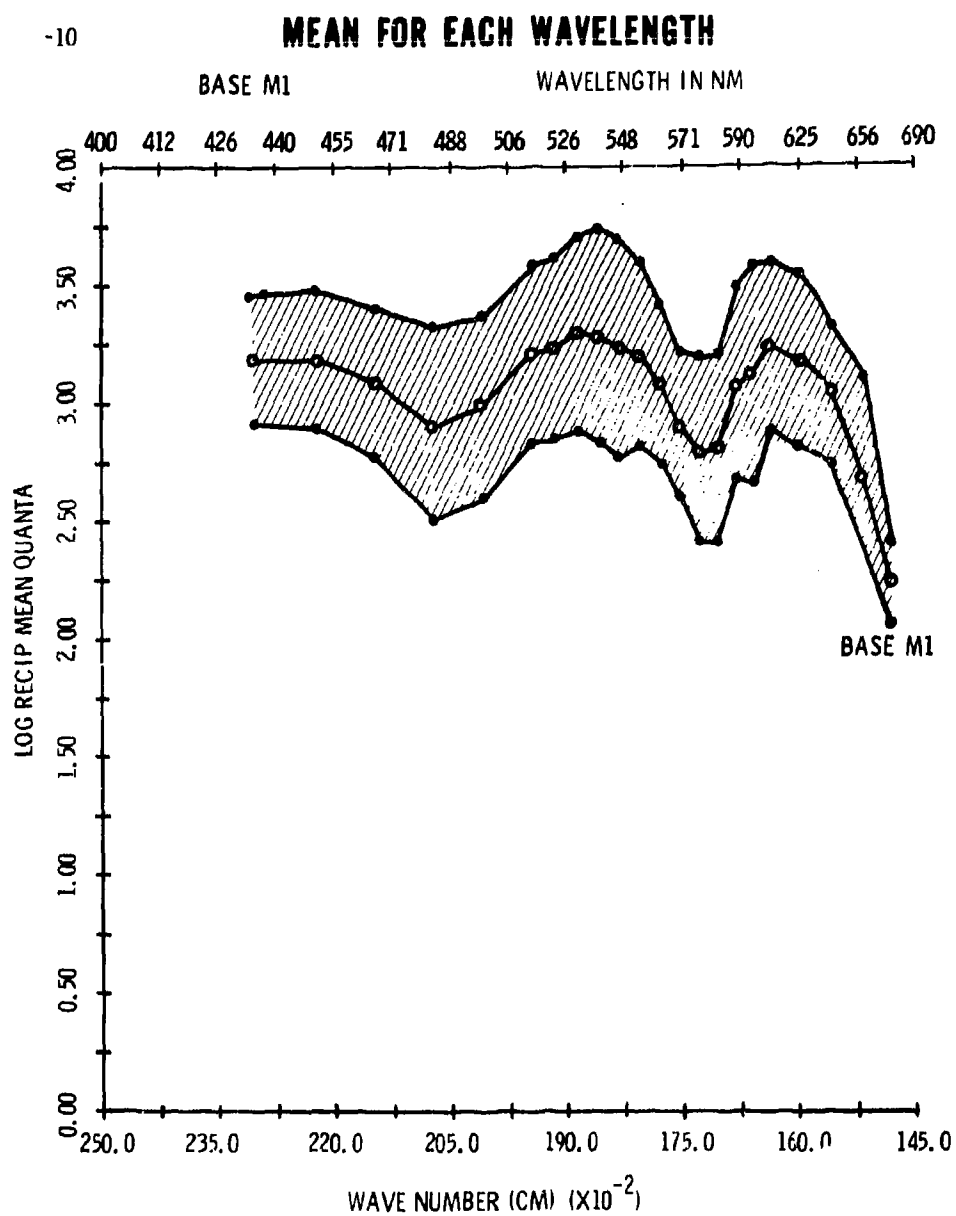


Fig. 7. Baseline spectral sensitivity of M1 for a 2° spectral flash against a 20°, 3000 Troland white background. The shaded area represents \pm one standard deviation.

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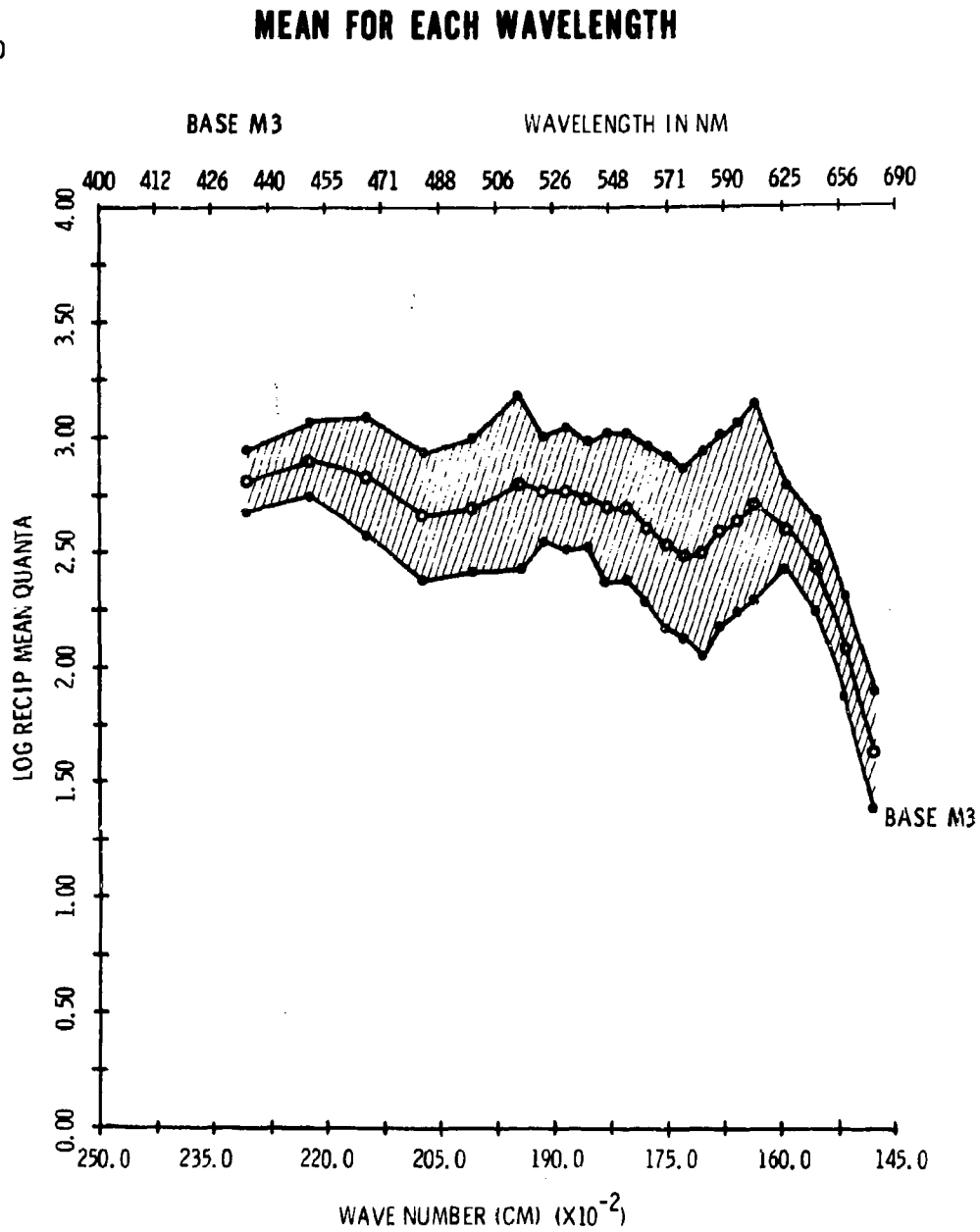


Fig. 8. Baseline spectral sensitivity for M3, same conditions as Fig. 7.

MEAN FOR EACH WAVELENGTH

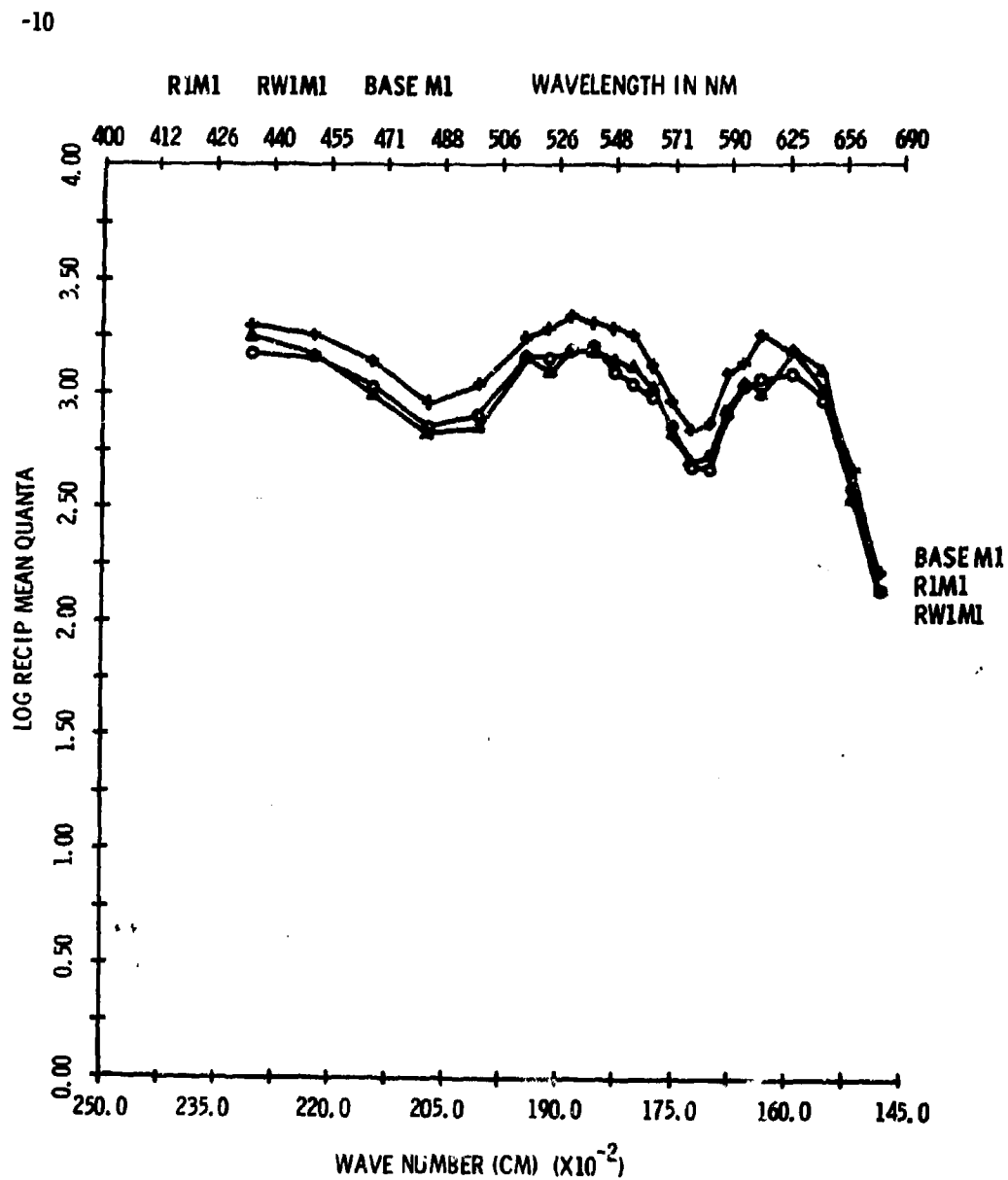


Fig. 9. The effects on spectral sensitivity of the addition of 100 Trolands of red light to the 3000 Troland white background.

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MEAN FOR EACH WAVELENGTH

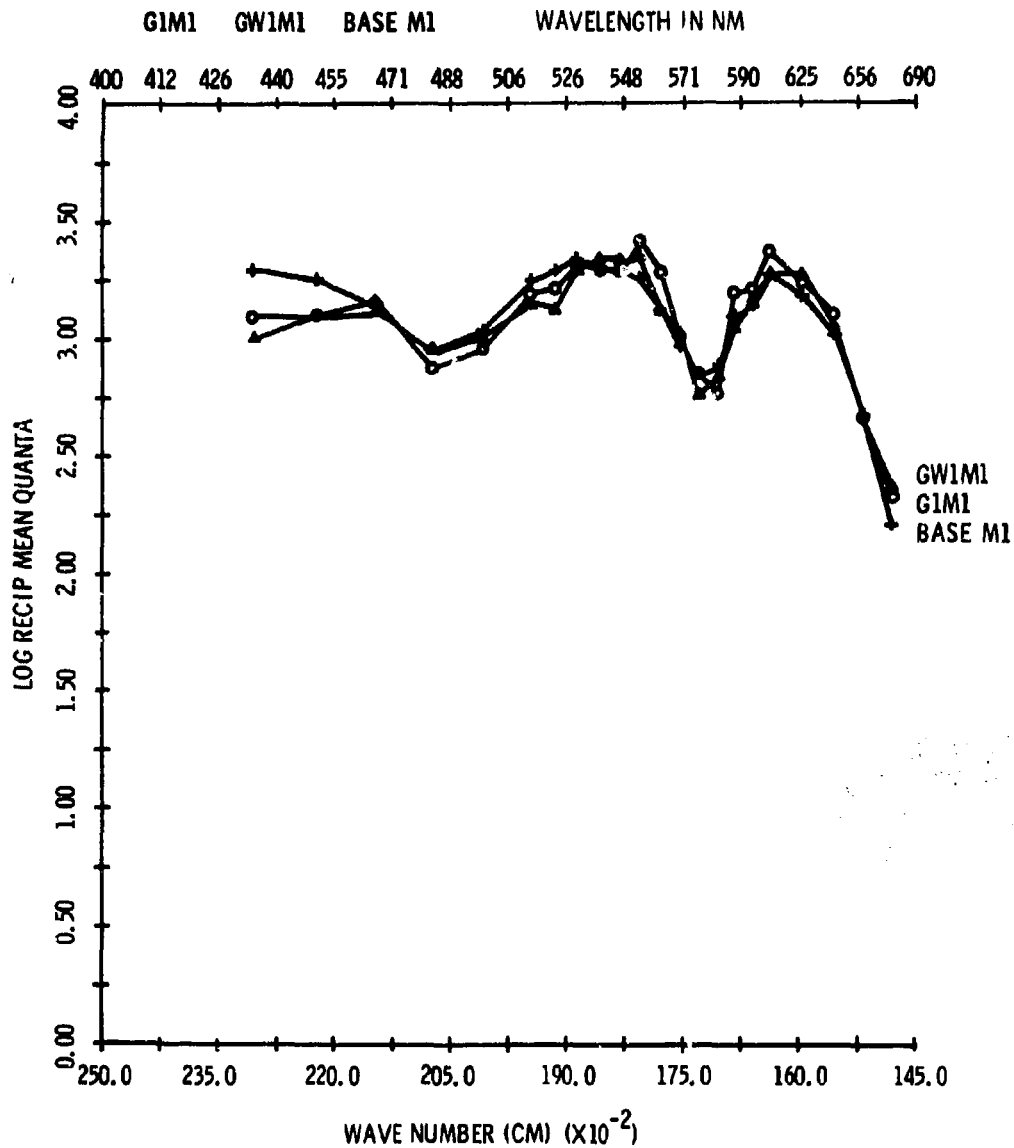


Fig. 10. The effects on spectral sensitivity of the addition of 100 Trolands of green light to the 3000 Troland white background.

MEAN FOR EACH WAVELENGTH

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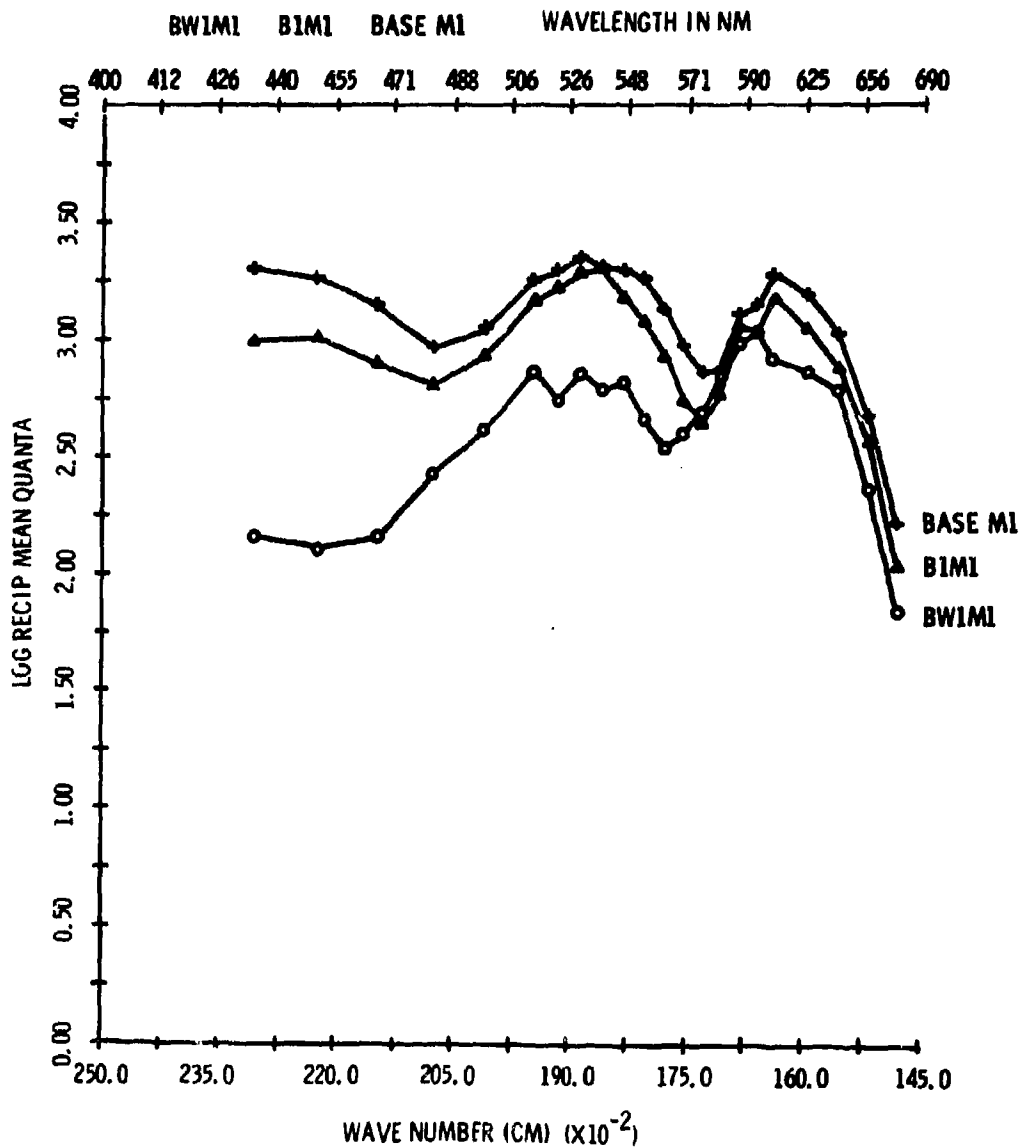


Fig. 11 The effects on spectral sensitivity of the addition of 100 Trolands of blue light to the 3000 Troland white background.

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MEAN FOR EACH WAVELENGTH

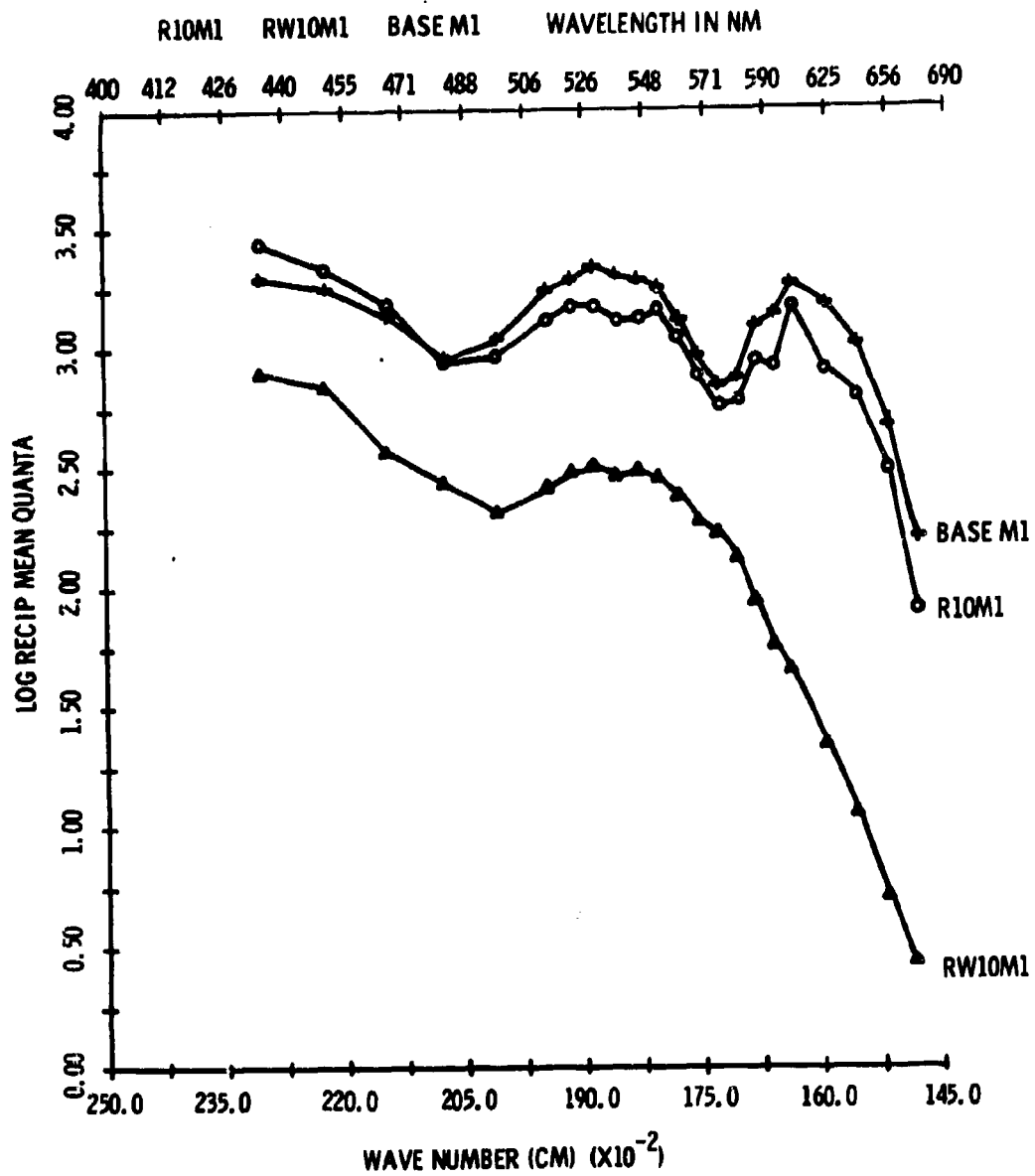


Fig. 12 The effects on spectral sensitivity of the addition of 10,000 Trolands of red light to the 3000 Troland white background.

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MEAN FOR EACH WAVELENGTH

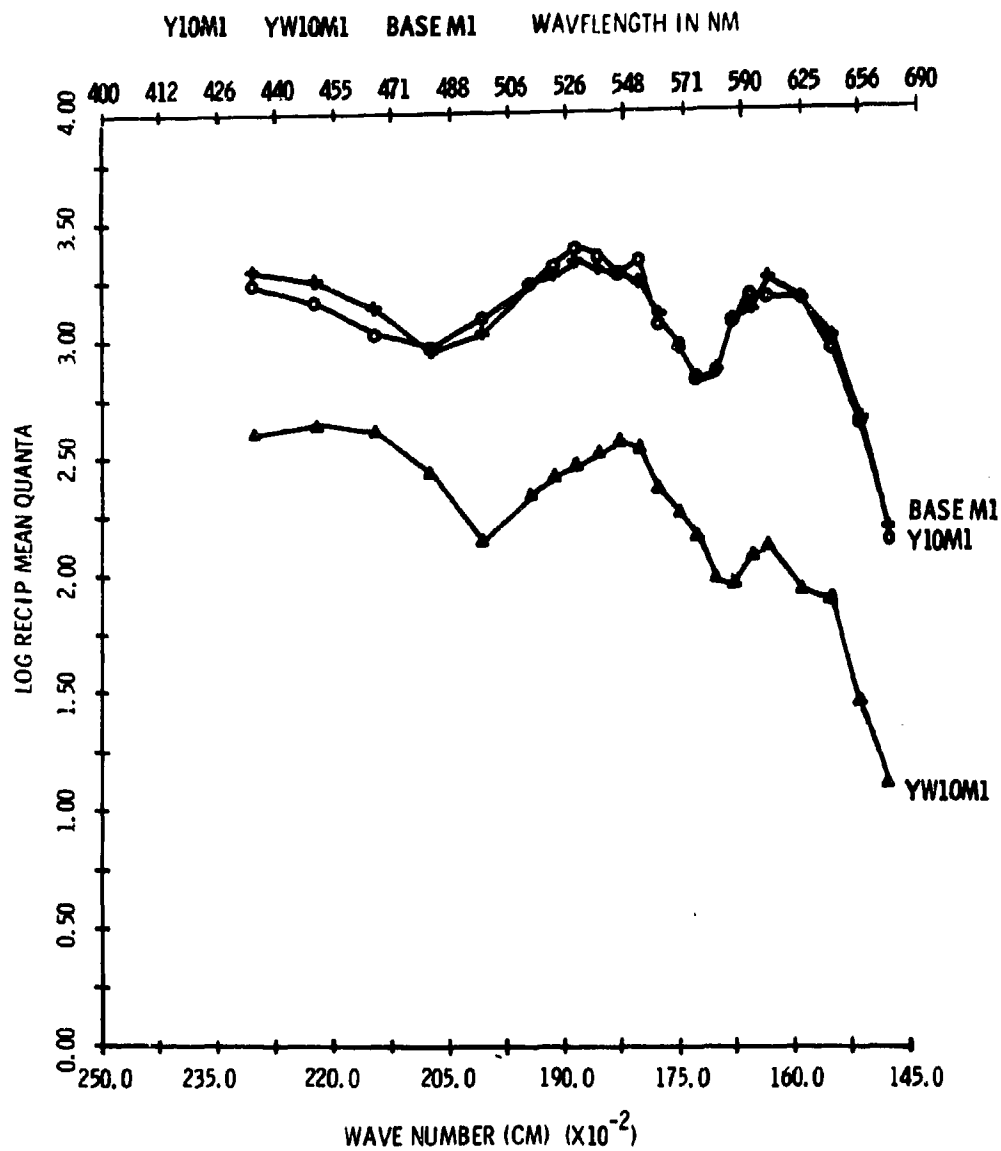


Fig. 13 The effects on spectral sensitivity of the addition of 10,000 Trolands of yellow light to the 3000 Troland white background.

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MEAN FOR EACH WAVELENGTH

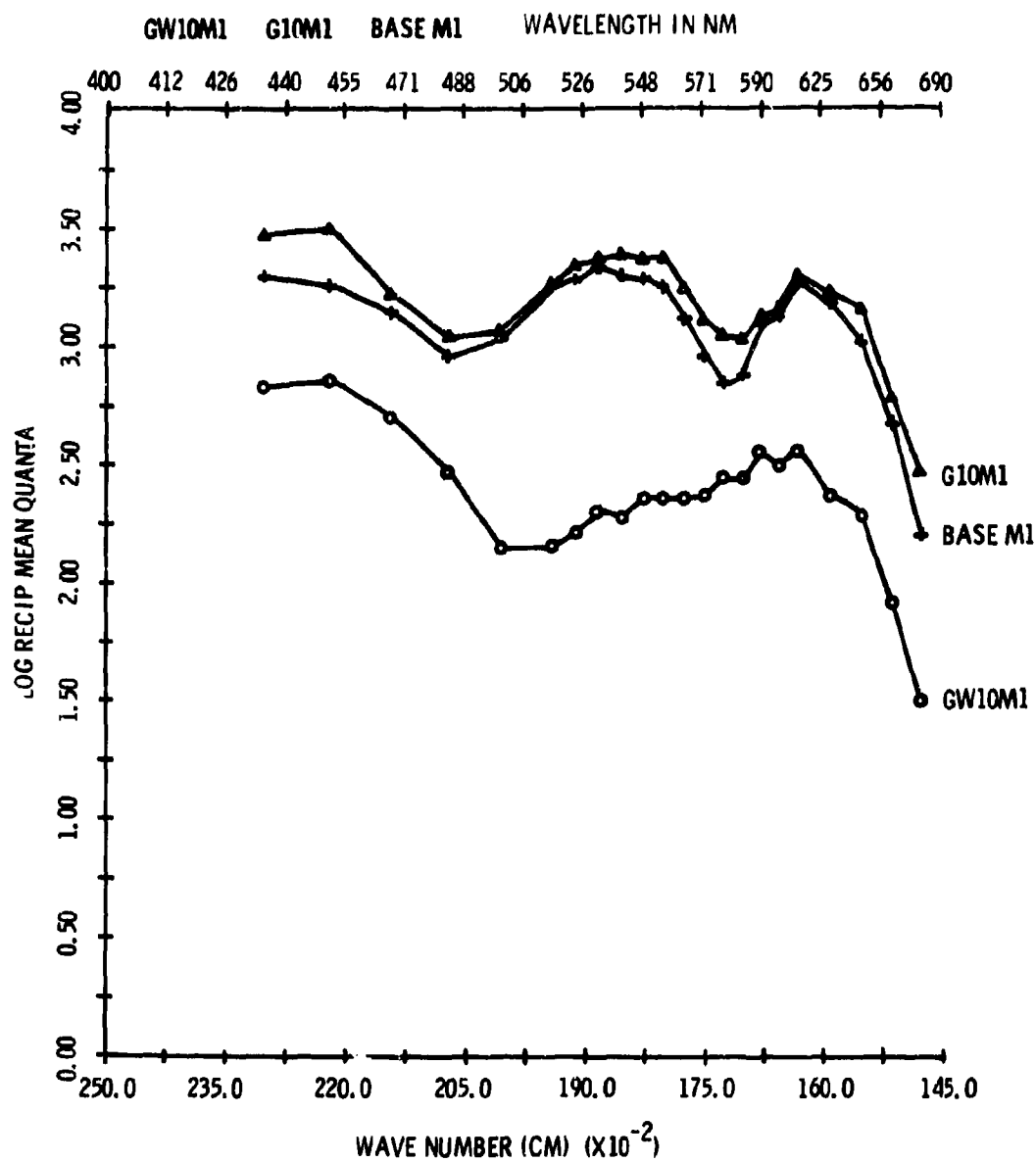


Fig. 14 The effects on spectral sensitivity of the addition of 10,000 Trolands of green light to the 3000 Troland white background.

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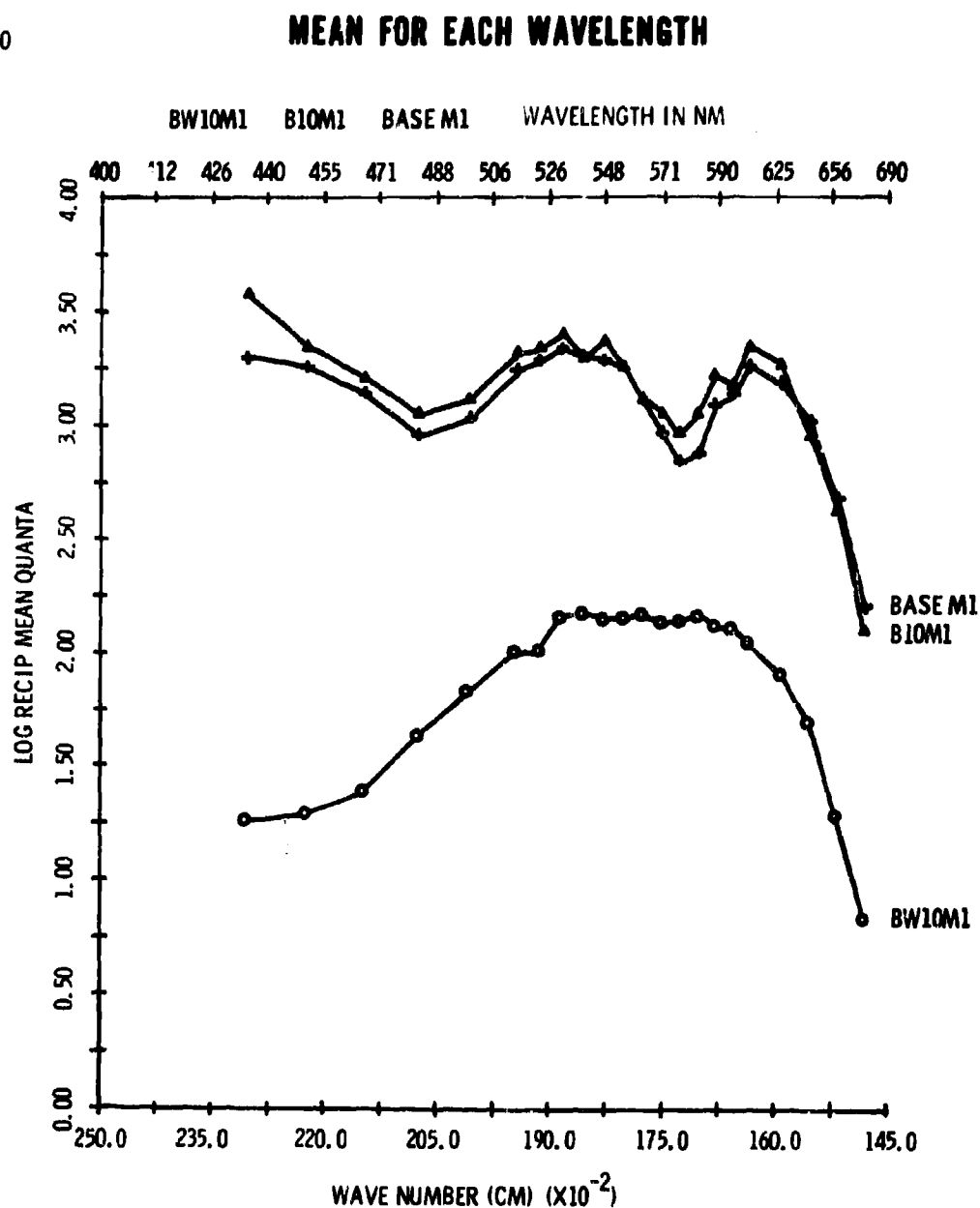


Fig. 15 The effects on spectral sensitivity of the addition of 10,000 Trolands of blue light to the 3000 Troland white background.

ELECTRORETINOGRAPHIC AND BEHAVIORAL
RECOVERY TIME OF CATS TO HIGH INTENSITY PHOTIC STIMULATION

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INTRODUCTION

The decrement in visual performance following exposure to intense photic stimuli has been termed flash blindness. Recent reviews^{1,2,3} of flash blindness studies have shown that human recovery time is dependent upon many variables. Among these are: the intensity of the target stimulus, the visual acuity required to detect or identify the target, the spectral distribution of both the adapting flash and the target, the energy of the adapting flash, and the retinal area stimulated.

However, exploration of the effects of intense photic stimulation upon human recovery times has been limited by the amount of energy which could be delivered safely to the eye of the subject. Therefore, it was considered desirable to determine the feasibility of using both behavioral and electroretinographic (ERG) responses of cats to visual stimuli as a measure of visual impairment.

The purpose of the present paper is to present the results of two studies of the recovery times of cats. The first will be a report of an operant conditioning technique and the second will consist of the results obtained by electroretinography.

CONDITIONING STUDY

Apparatus

The conditioning apparatus consisted of a 45 cm cubical plexiglas box with an elevated floor 10 inches above the bottom of the cage. Mounted in the floor, to the animal's left, was a circular pedal, 5 cm in diameter which extended 12 mm above the level of the floor. On the outside front of the clear plexiglas box was mounted a food tray which was accessible to the animal through a 10 cm square opening. The

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target was a 115 volt AC 15 watt clear tungsten filament lamp with a color temperature of approximately 2050°K. This was placed 15 cm behind an 11 mm diameter aperture. The target subtended a visual angle of 2-1/2°. Kodak neutral density filters were placed between the source and the aperture. The lamp house was mounted 10 cm outside of the front wall of the conditioning apparatus. Three GE No. 50 photoflash lamps were mounted above the target light, 15 cm from the cat's eyes and at the animal's eye level. Each flash lamp subtended a visual angle of 20° and yielded a total output of 95,000 lumen-seconds over a period of 60 ms. The peak output was determined to be approximately 5,000,000 lumens at 30 ms⁴. The total energy delivered to the corneal surface by each lamp was approximately 0.26 j/cm². A Gerbrands variable interval programmer (Model PT-1A) turned on the target lamp, while a Hunter decade interval timer (Model No. 100C) controlled the duration of the stimulus presentation. A ratio programmer (Gerbrands, Model RP-1) controlled the number of presses for the positive reinforcer. 196 mg P. J. Noyes cat-food pellets were delivered by a Gerbrands Model D pellet dispenser wired to the ratio programmer.

The conditioning apparatus was enclosed in a large (1.8 m x 1.2 m x 1.2 m) light tight chamber, equipped with a 100 watt tungsten-filament bulb and a small fan for air circulation. A second 100 watt tungsten-filament bulb was equipped with filters transmitting the infrared (beyond 900 millimicrons). An infrared scope was mounted on the exterior of the light-tight box.

Procedure

Three male cats*, 12-14 months old, were used in the present

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study. The cats were initially deprived of food for 48 hours. Each was then placed in the conditioning apparatus in a well-lighted room and allowed to eat ad lib from the food magazine for one hour. This phase lasted for five days, during which they were fed only while in the training box. The second phase of training occurred on Day 6 when the successive-approximations method of training bar-press behavior was instituted. The target light remained on throughout this stage at an intensity of 3.86 FC, with the 100 watt tungsten filament bulb providing ambient illumination (3.86 IA condition). This training continued until each cat sat directly in front of the food tray and pressed the pedal with his left front paw. After 28 days of training, one hour per day on a variable ratio ($\bar{x} = 4:1$) schedule, the discrimination training was instituted. In this sequence of trials, the animals were rewarded for pressing the bar in the presence of the target light (CS) which remained on for 10 seconds. A two minute delay of onset of the target stimulus was then introduced when the animal pressed the pedal in the absence of the stimulus. The animals were then trained to a 100-percent-correct response criterion.

In the final phase of training, the cats were placed in the dark room in their training apparatus. A variable interval ($\bar{x} = 1.5$ min) programmer was then used to present the CS for 5 second periods. The animals were reinforced on a 2:1 fixed ratio. Thus, the animals were required to maintain a relatively stable position with respect to the pedal, and to respond to the presence of the CS with at least two pedal depressions.

At two random times during each acquisition session of the conditioned response, the startle response of the cats to the firing of the flash bulbs was gradually adapted out by firing the flash bulbs

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at various distances (15 to 60 cm) from their eyes. After the tenth or twelfth flash, the cats did not show any noticeable startle response.

The flash-blindness-recovery testing began after 46 days of two 1-hour sessions per day of the discrimination training.

The cats were dark-adapted for 15 minutes, during which time no CS's were presented. After 15 minutes, the variable interval program of CS presentations was started and continued for an additional 15 minutes. At 30 minutes, one flash bulb was fired and simultaneously the target light was turned on and an electric timer was activated. The animal's recovery time was then taken as the second bar press in the presence of the CS. This procedure was also followed after 45 and 60 minutes in the apparatus. To eliminate the possibility that the animals were responding to positive after images resulting from the flash lamps, test trials were inserted in every tenth trial (approximately every third session) in which the flash bulb and timer were activated, but the target lamp remained out. In no test did the animals press the lever in the absence of the CS during a two minute observation period.

For each animal, 9 recovery-time trials were obtained for each of 5 target conditions; 3.86, .334, .027, .0027 foot candles and for 3.86 foot candles with the animal light-adapted (3.86 LA) by the continuous illumination from the 100 watt tungsten lamp. Each target condition was randomized with respect to sessions, however within each session the target conditions were constant.

RESULTS AND DISCUSSION

The means and standard deviations for each cat's recovery times are presented in Table 1. As can be seen from Table 1 and Fig. 1,

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the behavioral recovery time of cats D and M were similar, while cat W showed consistently longer recovery times.

The curves presented in Fig. 1 were approximately linear plots of recovery time, as a function of \log_{10} intensity. A least squares approximation of each curve yielded the following equations: Cat W, $Rt = -5.10 \log_{10} I + 21.12$; Cat M, $rt = -3.72 \log_{10} I + 15.48$, and cat D, $Rt_c = -4.00 \log_{10} I + 13.88$ (Rt = Recovery Time and I = Target Luminance).

The recovery time to the light-adapted condition as shown in Fig. 1 was faster for all animals than any of the dark-adapted conditions. This result was predicted on the basis of previous findings that with the adapting flash energy constant, the recovery time decreases as a function of increasing ambient and target illumination⁵. This condition was used as a further control to insure that the animals were responding to the appearance of the target stimulus.

A summary of the analysis of variance⁶ is shown in Table 2. The effects due to subjects were statistically significant ($P < .01$) and could be accounted for by the individual differences in the mean recovery times (vertical curve displacement) as seen in Fig. 1. The main effect due to luminance was highly significant ($P < .001$). Neither the effect of sessions (replications) nor the interactions were found to be statistically significant.

The similarity found between the slopes of the individual curves together with the non-statistically significant subjects x intensity interaction indicates that the effect of luminance was consistent for each animal. The results indicated that as the luminance of the target is decreased, recovery times increase when the adapting stimulus remains constant. These results are consistent with findings

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by other investigators using human subjects⁷.

ELECTRORETINOGRAPHY

In the second study, we wished to determine the effects of high intensity photic stimulation upon the cat ERG. This was done since we felt that increasing the energy or varying the wavelength of the flash blinding stimulus would cause disruption in the behavior of the cat. With this disruption, we would then not be confident that our recovery time decrements were due to the stimuli alone or to distractions induced by changes in the energy and wavelength of the stimuli. Further, since the conditioning procedure was extremely time-consuming, a parametric study of the effects of variations in the wavelength of both the flash blinding stimuli and the target stimuli, would have been prohibitive.

Procedure

Animal Preparation

Four adult male cats were used in the present experiment. Each was between 1-1/2 and 2 years of age and weighed 8-10 pounds. They were selected on the basis of similarity of coloring of the tapetum lucidum and tapetum nigrum in the central retinal area. Fundus photographs were taken of both eyes. Each eye was examined with a binocular indirect ophthalmoscope prior to and following each session to insure that no visible pathology was present. Two drops of 1.0 percent atropine sulfate was placed in each eye to dilate the pupils and paralyze the ciliary muscles. An intravenous injection of 100 to 150 mg of sodium pentobarbital (nembutal) was followed by 50-75 mg administered interperitoneally. Several drops of 0.5 percent Tetracaine HCl were put into the eyes. A suture was then placed in each

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eye at the 12 o'clock position, 1 mm superior to the corneal scleral junction. This enabled us to manipulate and hold the eye in a fixed position throughout the experimental session. A plastic, non-conducting lid retractor was then inserted into each eye. Cotton wick electrodes, soaked in 5 percent saline solution, were placed at 6 o'clock, 1 to 2 mm below the inferior margin of the corneal-scleral junction of each eye. An intra-dermal electrode was inserted into the skin of the animal, 5 mm nasally and 1 cm superior to each eye. A ground electrode was fastened to the external margin of one ear.

Apparatus

The animal's eyes were aligned with the apparatus so that the focal point of the light of both the illuminator and the Xenon flash lamp (Fig. 2) fell on the same spot on the corneal surface and stimulated the same retinal areas. A collimated beam from the microscope illuminator was divided into two paths by a 50 percent reflecting mirror. One path led directly to the right eye, while the second was reflected in the left eye. At the right eye, the luminance of the microscope illuminator was controlled by means of a neutral density wedge. A motor driven rotating sector disk was inserted into the light path between the shutter and the illuminator. The disk rotated at 1 revolution per second and produced a flash of 30 milliseconds duration. The Xenon arc lamp system was mounted on the optical bench and hinged so that it could be lowered or raised into the light path of the right eye. The Xenon lamp power supply system was set at 1.6 KV, 600 μ fd at 500 μ h for all exposures. A blackened disk calorimeter, placed at the focal point of the beam, enabled us to equate the monochromatic filter energies directly with each other and with "white" light. Five monochromatic filters were used. These were: blue

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($\lambda_{\max} = 456 \text{ Nm}$), blue-green ($\lambda_{\max} = 485 \text{ Nm}$), green (Kodak XI, $\lambda_{\max} = 515 \text{ Nm}$), yellow (Kodak filter 15, transmitting 89 percent above 575 Nm) and red (Kodak 25 cutoff below 600 Nm with 80 percent transmission above 620 Nm). The neutral density wedge was used to adjust the energy levels of all stimuli to equality. The disk calorimeter was 1 cm diameter with a conversion factor of 0.173 j/mv. The diameter of the spot size at the focal point on the corneal surface was 2 mm. The equated energy for all wavelength conditions and "white" light was calculated to be 0.15 j/cm² and the duration of the flash was calculated at $\theta_{1/3}$ as 1030 μsec for the Xenon lamp. The compensated equivalent luminance for the ERG stimulus provided by the microscope illuminator was approximately 5,080 mL when measured by a Macbeth Illuminometer at the corneal surface. The energy levels for each ERG stimulus condition were equated in the same way with the same monochromatic filters and neutral density wedge used for the adapting conditions. Electroretinograms were recorded on two low level-high gain AC amplifiers of a Grass Model 7A polygraph, equipped with a 1-second time-marker. A selenium photoelectric cell was positioned on the shutter and each light pulse was monitored through the polygraph system.

Method

For each cat a 6 x 6 matrix was developed consisting of the six ERG stimulus conditions and six adapting or flash blinding conditions. Each animal was then dark adapted for 5 minutes. Following this, a 2-minute ERG baseline was obtained for the recovery wavelength used. This baseline yielded consistent b-wave amplitudes after the first 10 seconds of exposure. The final 90 seconds were used as the baseline with which recovery was compared. The animal was then flash blinded

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and the same ERG stimulus was again presented to the exposed eye. A total of 36 combinations of ERG stimulus and adapting wavelengths were presented in a random order in two sessions for each cat.

The height of the b-wave of the cat's ERG was measured in mms of pen deflection and transformed into microvolts. The baseline data obtained for each animal on each ERG wavelength stimulus prior to flash blinding was used to compare recovery of the ERG. For all 36 combinations, the means of 15-second time blocks were computed for the first five minutes or until the animals' post-flash ERG equaled the pre-flash ERG. The means of 30-second blocks were obtained over the next 5 minute period. For recoveries in excess of 10 minutes, the means were computed for every 60-second block of ERGs. Since the ERG was considered relatively stable for each animal but differed between animals, the recovery of each animal was followed by computing the percentage of the original ERG b-wave height (post-flash b-wave height/pre-flash b-wave height x 100) for each of the time blocks. The percent ERG recovery was plotted as a function of time for each animal for each of the 36 combinations. From these, six points were selected. These were the JND, or the time required for two successive ERG b-waves to be just-noticeably-different from the noise level of the apparatus, and at 10, 25, 50, 75 and 100 percent recovery.

RESULTS AND DISCUSSION

A summary of each of the six recovery levels is shown in Tables 3 and 4. The rows in each matrix of both tables represent the wavelength of the ERG stimulus while the columns show the wavelength of the adapting stimulus. The units in Table 3 are in seconds and are the means for the four animals. As is apparent from this table, the

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time it took to recover from adapting wavelengths of 456 and 485 Nm was significantly greater than the recovery to 620, 575, 515 Nm and "white" conditions. The units in Table 4 show the relative effectiveness of each wavelength in producing flash blindness when compared to the red adapting condition. In this table it can be noted that for the JND matrix, the 456 Nm adapting condition was from 11 to 47 times more efficient at producing delays in the start of recovery of the ERG than was the red adapting condition. These effects were even more apparent at the 100 percent ERG recovery level, where for an adapting flash of 485 Nm, it took an average of 12³/₄ seconds to recover fully to the 485 Nm ERG stimulus, while for the 620 Nm adapting condition, the mean recovery time for the 485 Nm ERG stimulus was only 19 seconds. This is a factor of 65:1, indicating the relative efficiency of this wavelength in the production of flash blindness.

Fig. 3 shows the recovery time in log₁₀ seconds as a function of the ERG stimulus wavelengths for the JND, 10, 25, 50, 75 and 100 percent recovery criteria for each of the six adapting wavelengths. From this figure, it can be seen that the difference between the blue (456 Nm) and blue-green (485 Nm) adapting energies is low, except at the JND criteria, where the recovery time to the blue-adapting stimulus is slightly (but not significantly) higher than that produced by the blue-green adapting stimulus. At the JND criterion, there are no significant differences between green (515 Nm), yellow (575 Nm) and red (620 Nm) and white adapting stimuli. The differences between the blue and blue-green curves and the remaining curves, while not remaining constant, show separations of more than one log unit. It is also apparent that as the recovery criteria are raised from the JND level to the 100 percent recovery level, the recovery times appear to fall

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into three distinct groups. The longest recoveries are still the result of the blue and blue-green adapting conditions, but the green, white and yellow now appear to be distinctly separate from the red adapting condition.

As is apparent in Fig. 3, the differential effects of the ERG recovery stimuli were negligible. In all cases, there were no differences in the recovery time of the ERG due to manipulation of the wavelength of the ERG stimulus. Thus, the recovery times at any ERG wavelength stimulus, i.e., 486 Nm, were the same as any other ERG stimulus wavelengths for the same adapting stimulus. The absence of slopes indicates that there was little, if any interaction between the adapting wavelengths and the ERG stimulus wavelengths.

These findings can be interpreted in two ways: First, Granit's^a description of the absorption characteristics (wavelength sensitivity) of rhodopsin, the photochemical substance found in mammalian retinal rods, shows a peak of absorption at about 502 Nm. The curve shows that little absorption occurs at either 575 or 620 Nm, while at 456 and 485 Nm, it approaches 80 and 95 percent respectively. It can thus be postulated that at the higher wavelengths, the amount absorbed by the rhodopsin is negligible and represents a very small portion of the available photo-pigment. Thus, recovery is more rapid as the proportion of energy absorbed by the retina decreases. Conversely, at the lower wavelengths which coincide with the region of maximal absorption of rhodopsin, an intense flash would cause more photochemical conversion of rhodopsin than had occurred at the higher wavelengths. This results in longer recovery times due to the reduction of retinal sensitivity resulting from the decrease of available rhodopsin necessary to initiate a retinal response. However,

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there were apparently no differences between the recovery times to green, white and yellow adapting stimuli where according to this hypothesis green (515 Nm) should yield the same, or longer recovery times than blue (456 Nm). This may partially be accounted for by noting the spectral transmittance characteristics of the green (Kodak XI, No. 11) filter used in the present study. This filter shows a maximum transmittance at 515 Nm of approximately 60.2 percent with approximately 30 percent at 485 Nm and 2 percent at 455 Nm. Above 515 Nm, a much larger amount of energy is transmitted than below this point, such that 15 percent of the energy is still transmitted at 620 Nm. This relatively greater amount of energy transmitted above 515 Nm would tend to decrease the amount of bleaching, since the absorption above 515 Nm is far less than below 515 Nm. The "white" adapting stimulus used in the present study, when averaged, would also peak in the green, although with a wider distribution across all wavelengths.

The second explanation is based upon the findings of Wald⁹ and others of three cone pigments with different absorption maxima. In the primate the three cone pigments were found to have maximum absorption at 445, 535 and 570 Nm. The cat has been shown to possess both rods and cones in its retina, although the former are in greater abundance and the latter in a lesser number than in the human eye. Absorption maxima at 450, 540 and 610 Nm were found by Granit⁸ for the light-adapted cat eye. He also indicated that the scotopic-photopic dominator curve shift for the cat's eye was almost identical to that of man (p. 122). In the present study, the differences in recovery times for the adapting stimulus wavelengths at each ERG stimulus wavelength may be the result of the selective absorption of

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the three cone pigments. Thus, the maximum at 450 Nm found for the cat's eye would reflect the operation of the "blue" cones at the 460 and 485 Nm adapting wavelengths, the "green" or 540 Nm maximum at the green, white and yellow adapting wavelengths and the "red" or 610 Nm maximum for the red adapting condition. The variability in recovery times would therefore be a function of the number of retinal elements maximally responsive at each of the three wavelengths. The ERG is a response of the retina as a whole to light stimulation. With fewer "red" cones, the effect of adaptation to red light would be less than adaptation to other wavelengths, since only a fraction of the total available cone pigments has been affected. Conversely, if the "blue" cone pigment was present in greater quantity than the "red" or "green", recovery would be longer, due to the greater amount of pigment bleached.

Of the two interpretations of the wavelength differences observed in this study, the latter appears to be the more tenable, since the experimental system was such as to preclude a low dark-adaptation (scotopic) level. The one-pulse per second flicker at the luminosity used to generate the ERG would contribute to a state of light adaptation. Thus, cone responses should be more influential than the rod responses in the production of the ERG decrement following flash blindness.

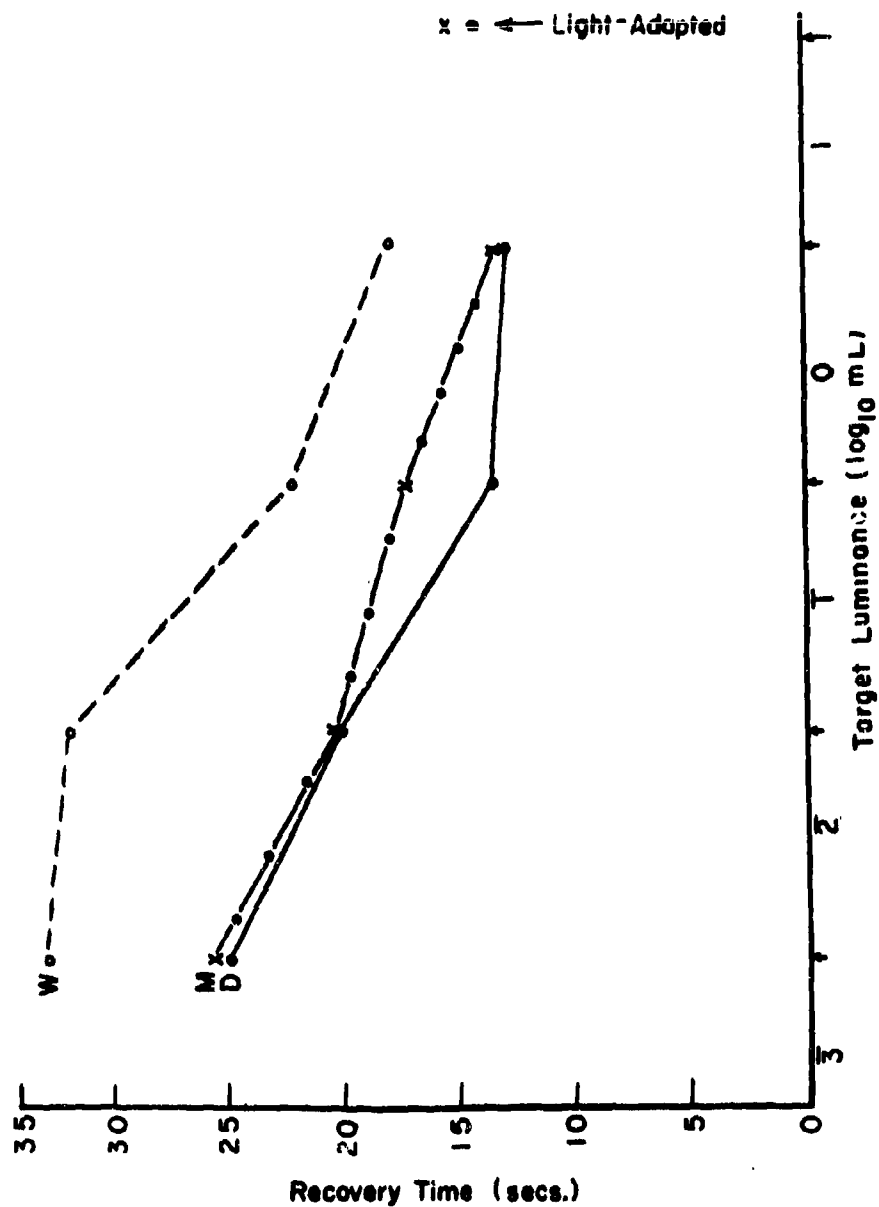
Several conclusions can be drawn from this study. 1. The production of flash blindness in cats is largely dependent upon the wavelength of the adapting flash. 2. Maximum visual impairment occurs when the adapting flash is in either blue or blue-green, regardless of the ERG stimulus wavelength. 3. The blue and green stimuli were up

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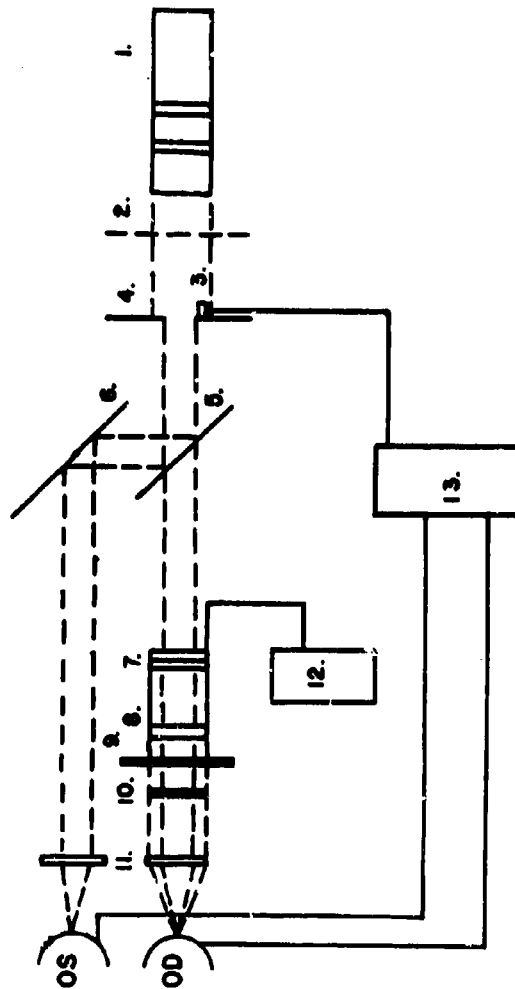
65 times more effective in producing flash blindness than were the red, yellow, white and green adapting flashes. 4. No differences were found between the wavelengths of the ERG stimuli used to measure the recovery time of the cat.

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- * In conducting the research described in this report, the investigator adhered to the "principles of laboratory animal care" as established by the National Society for Medical Research.

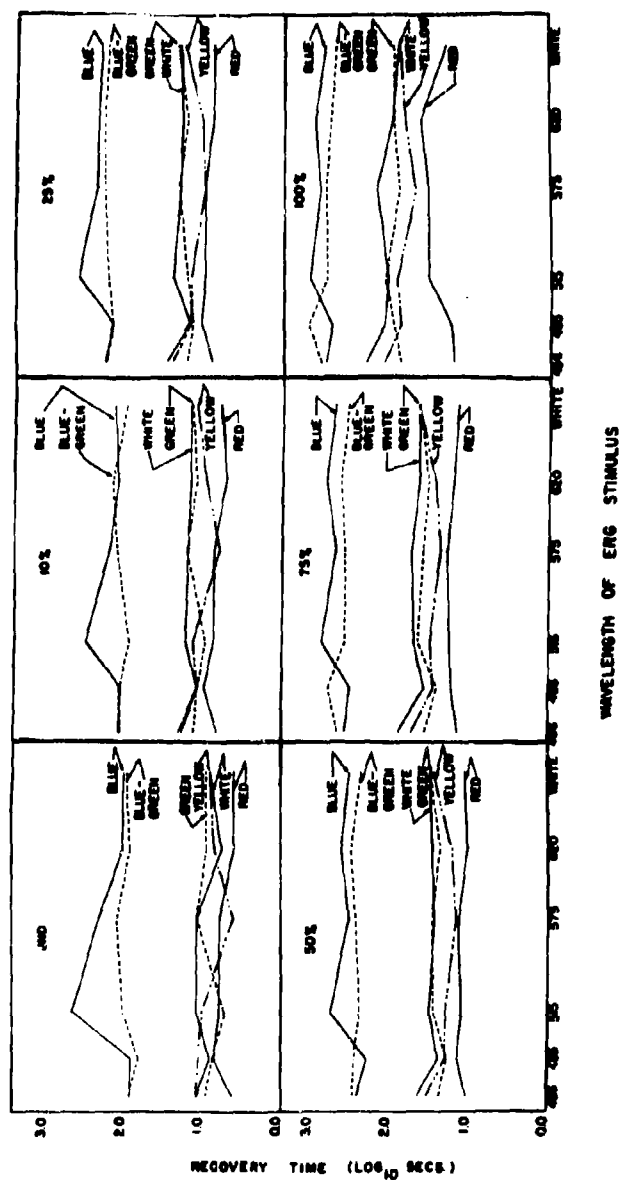


1. Recovery time of 3 cats as a function of \log_{10} target luminance following 15 minutes dark adaptation. Points to the extreme right show recovery times for the light-adapted condition.



- | | | |
|------------------------------|--------------------------------|-----------------------------|
| 1. UNIVERSAL ILLUMINATOR | 5. 50% TRANSMITTANCE MIRROR | 10. MONOCHROMATIC FILTER |
| 2. FLICKER DISK | 6. MIRROR | 11. 50 MM BICONVEX LENS |
| 3. PHOTOELECTRIC CELL | 7. FX42C XENON FLASH TUBE | 12. 1.5KV D.C. POWER SUPPLY |
| 4. ALPHA-X SYNCHROMATIC IRIS | 8. 55MM BICONVEX LENS | 13. GRASS POLYGRAPH |
| | 9. KODAK NEUTRAL DENSITY WEDGE | |

2. Schematic diagram of apparatus.



3. Mean recovery time in \log_{10} seconds as a function of the wavelength of the ERG stimulus for each adapting wavelength at each of the six criteria.

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Table 1. The Means and Standard Deviations of the Recovery Times (in seconds) for the Three Cats for the Five Target Conditions

		<u>Target Intensity (Foot Candles)</u>				
<u>Cat</u>		<u>3.86 (IA)</u>	<u>3.86</u>	<u>.334</u>	<u>.027</u>	<u>.0027</u>
D	\bar{x}	6.73	12.99	13.57	20.21	24.86
	σ	4.25	4.82	5.62	9.15	12.48
W	\bar{x}	6.48	18.03	22.36	31.91	32.71
	σ	2.22	7.01	6.51	16.91	12.97
M	\bar{x}	5.46	13.51	17.40	20.37	25.63
	σ	1.11	5.43	8.48	9.97	10.24

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Table 2. Summary of Analysis of Variance for the Recovery Times of Cats for the Five Intensities and Three Sessions (Replications). [Winer, p. 213]

Source	df	SS	Mean Square	F	Level of Significance
Subjects	2	1,177.20	588.60	5.73	< .01*
Intensity	4	7,596.07	1,899.02	18.50	< .001**
Sessions	2	30.55	15.28	0.15	N.S.
Subjects x Intensity	8	466.82	58.35	0.57	N.S.
Subjects x Sessions	4	318.28	79.57	0.78	N.S.
Intensity x Sessions	8	713.73	89.22	0.87	N.S.
Subjects x Intensity x Sessions	16	735.47	45.97	0.45	N.S.
Error	90	2,240.65	102.67		
Total	134	20,278.77			

* $f\ 2, 60 = 4.98$

** $f\ 4, 60 = 5.31$

WAVELENGTH OF ADAPTING STIMULUS

	JND						10%						25%					
	456	485	515	575	620	WHITE	456	485	515	575	620	WHITE	456	485	515	575	620	WHITE
456	81	83	9	12	4	12	105	108	12	16	6	17	167	164	17	26	8	30
485	77	62	7	11	7	6	105	81	11	11	9	11	147	147	14	15	11	16
515	282	101	5	10	6	12	297	119	9	13	7	16	388	169	17	15	10	25
575	125	120	12	4	6	12	151	137	16	6	7	15	241	191	21	10	10	21
620	102	91	9	7	4	9	115	90	12	9	5	14	233	193	17	11	8	20
WHITE	97	87	9	8	4	8	129	102	14	12	6	14	210	168	23	19	8	21

WAVELENGTH OF ERG STIMULUS

	50%						75%						100%					
	456	485	515	575	620	WHITE	456	485	515	575	620	WHITE	456	485	515	575	620	WHITE
456	272	305	24	35	11	46	383	468	36	54	14	79	701	815	79	135	17	225
485	239	296	19	20	14	25	328	630	26	29	17	37	600	1234	101	83	19	131
515	580	253	28	20	13	32	780	387	46	32	18	51	1170	701	133	92	37	121
575	336	283	30	15	14	28	511	402	40	24	20	56	893	747	90	56	38	173
620	422	320	24	17	11	30	680	455	35	28	17	46	1076	668	105	75	49	113
WHITE	341	247	33	29	12	32	532	369	46	47	15	47	771	573	105	90	23	94

Table 3. Mean recovery times in seconds for the six criteria at each combination of adapting stimulus and ERG stimulus wavelengths.

JND

10% 25%

WAVELENGTH OF ADAPTING STIMULUS (Nm)

	456	485	515	575	WHITE	620	456	485	515	575	WHITE	620	456	485	515	575	WHITE	620
456	20	21	2	3	3	1	18	18	2	3	3	1	23	23	2	3	4	1
485	11	9	1	2	1	1	12	9	1	1	1	1	13	13	1	1	1	1
515	47	17	1	2	2	1	42	17	1	2	3	1	39	17	2	2	3	1
575	21	20	2	1	2	1	22	20	2	1	2	1	24	19	2	1	2	1
WHITE	24	22	2	2	2	1	22	17	2	2	2	1	26	21	3	2	3	1
620	26	20	2	2	2	1	23	18	2	2	3	1	29	24	2	1	3	1

STIMULUS (Nm)

50% 75% 100%

WAVELENGTH OF

	456	485	515	575	WHITE	620	456	485	515	575	WHITE	620	456	485	515	575	WHITE	620
456	25	28	2	3	4	1	27	33	3	4	6	1	41	48	5	8	13	1
485	17	21	1	1	2	1	19	37	2	2	2	1	32	65	5	4	7	1
515	45	19	2	2	2	1	43	22	3	2	3	1	32	19	4	2	3	1
575	24	20	2	1	2	1	26	20	2	1	3	1	24	20	2	1	5	1
WHITE	28	21	3	2	3	1	35	25	3	3	3	1	34	25	5	4	4	1
620	38	29	2	2	3	1	40	27	2	2	3	1	22	14	2	2	2	1

Table 4. Relative recovery times at each adapting wavelength when compared to the 620 Nm adapting stimulus for each ERG adapting stimulus at each recovery criterion.

USE OF ELECTRORETINOGRAPHY IN THE STUDY OF FLASH BLINDNESS IN ANIMALS

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The development of intense sources of light, as for example, nuclear explosions and lasers, has created the need to study the effects of such light on the eye. The present work was directed primarily towards problems of flash blindness, that is, temporary degradation of vision and not with thermal injury. This study required the selection and development of suitable intense light sources and, because of the possibility of injury to human subjects, the development of methods that would permit use of animals as the subject. Electroretinography (ERG) was selected as the technique for assessing visual loss.

A considerable amount of information is available on the phenomenon of dark and light adaptation but not with the intense light anticipated for use in these studies. The problem then is to determine whether the effects on vision with intense light are merely an extension of changes in adaptation or related to an entirely different process.

In dark adaptation of the human eye, the visual sensitivity increases rapidly with time until a plateau is reached after about 5 minutes. Little recovery occurs during the next 10 to 15 minutes, at which time sensitivity increases once again until maximum sensitivity is reached in about 30 minutes. Data taken from a dark adaptation curve by Rushton¹ was replotted with log-time instead of linear time as the abscissa, Figure 1. The rapid or cone phase [1] and the slow or rod phase [3] of dark adaptation are both linear when the log-threshold is plotted against log-time. The initial changes in sensitivity during both dark and light adaptation are very rapid and reversible. The course of recovery from exposure to light depends upon the spectral quality, on the intensity and on the duration

of the adapting light. The threshold changes during the greater part of light adaptation are explained on a basis of bleaching of the retinal pigments by light, that is, conversion to an insensitive form of the pigment during light adaptation of the eye and regeneration of the sensitive form of the pigment during dark adaptation.² There are several cone pigments, chlorolabe, erythrolabe and probably cyanolabe¹; the primary rod pigment is rhodopsin.³ The range of sensitivity in the human eye is very great, perhaps 17 log units including 3.5 log units for cones.^{1,4} For animals where measurements are based essentially on objective measurements, in contrast to man, where subjective end points are used, ranges of visual sensitivity appear to be variable from species to species and less than that for humans, e.g., ~ 5 log units for the rat.⁴

Dark adaptation depends somewhat on the amount of pigment bleached^{1,5} but other factors must be considered.^{5,6,7} The process appears to consist of two parts, an early rapid change, with the delay attributed to neural response, and a slower change, related to regeneration of pigment. For rats in which the amount of rhodopsin bleached was small, Dowling⁴ found the delay was relatively short, not more than 10 minutes; when the amount of rhodopsin bleached was appreciable, there was in addition a longer lasting delay, up to 2 or 3 hours. Hagins⁸ found that in rabbits, for flashes of about 1 millisecond duration, only about half the rhodopsin could be bleached, regardless of the intensity of the irradiance, and Rushton⁹ found that for humans, recovery was the same for short intense flashes and for relatively long steady light, even though the amount of rhodopsin bleached was much greater for the latter. Dowling and Hubbard¹⁰ considered this to be due to isomerization of 11-cis retinal

attached to opsin to form various unstable intermediates, all of which are trans-retinal, and the reconversion of some of the trans form back to the cis form if the exposure time is not long enough to permit the separation of the trans form from the protein. Using rats in which the early rod response is not obscured by the faster cone response, they found that after the short intense flash the rhodopsin is regenerated rather slowly for about 30 minutes and then proceeds at the same rate as after the longer exposure. Rushton⁵ found for humans and Dowling¹¹ for rats that after the fast neural delay the visual threshold depended on the rhodopsin content of the retina, and moreover, the logarithm of the threshold varied linearly with that content. On that basis, log threshold is generally taken as a significant measure of visual sensitivity.

Some of the drawbacks to the use of ERG threshold measurements as the criterion for visual function after flash blinding are (1) ERG responses represent a summation of potentials from different areas of the retina, and it is difficult especially in primates with mixed retinas to separate responses as to specific contribution from these areas and receptors; (2) ERG threshold data are not an effective measure of visual acuity and (3) animals must be anesthetized in order to adequately measure ERG thresholds; this has the advantage that the eye can be carefully aligned in the light source but has the disadvantage that the influence of the anesthetic is uncertain. However, since ERG measurement does not require subjective evaluation, its use with animals, aside from convenience, serves to justify its use based on the following observations:

1. There is a direct dependence of threshold sensitivity on the amount of rhodopsin present in the retina. The logarithm of the

threshold is a linear function of the rhodopsin concentrated; this was determined by psychophysical measurements by Rushton⁵ for humans and by ERG for rats by Dowling.¹¹

2. There is a fairly direct correlation between the sensitivity of the human eye as measured by psychophysical and ERG techniques. During dark adaptation the threshold determined by these two methods was similar as shown by Johnson and Riggs¹² and Best and Bohnen¹³. The former found similar but not identical trends.

Armington¹⁴ found similar dependence on wavelength for the psychophysical threshold and energy to produce constant ERG amplitude.

3. Blough^{15,16} showed that visual sensitivity in the pigeon varied with wavelength in similar ways when measured by electrical response and by behavioral techniques. He compared his behavioral results with those obtained by Granit¹⁷ and Donner¹⁸ who measured electrical discharges from retinal receptors with micro electrodes. For both light and dark adapted eyes there was good agreement. His spectral sensitivity curves also agreed fairly well with absorption curves of rhodopsin and iodopsin.

These three sets of observations constituted the basis for use of ERG when these experiments were started. Also, the use of ERG represented one of few readily available methods by which flash blindness could be studied at levels which would be too hazardous for man. A variety of animals was used in an attempt to study separately the response of rod and cone visual cells to these bright flashes.

For this report, radiometric units are used for expressing energy and power.

INTENSE LIGHT SOURCES

Two sources of intense light were used, a carbon arc for generating pulse durations of from 1 millisecond to several seconds and a xenon flash system for pulses of from 50 microseconds to 1 millisecond. The xenon system was used for the experiments with monkeys, the carbon arc for all other species. Both devices are described in more detail elsewhere.^{19,20}

Carbon Arc

The arc was a Peerless Hy-candescent arc with 13.6 and 12.0 mm diameter carbons, positive and negative respectively, operated at 75 volts, 175 amperes, DC. The optical system is shown in Figure 2. The intensity was controlled with the iris diaphragm and alternated by appropriate neutral density filters. Camera shutters were used to select pulses of 1, 10, 100 and 1000 milliseconds, automatically, and longer pulses were obtained by an external timer.

The flux was measured with a Gardon foil radiometer²¹; the sensitive diameter was 0.9 mm, the response time 10 milliseconds and the spectral response flat from 0.2 to 2.0 μ . The flux distribution across the image at the cornea was measured with a 0.05 mm diameter light pipe and a photomultiplier.

The beam angle was variable, up to 37°, and the arc image at the cornea was 8.0 mm in diameter; the wide angle beam was used to irradiate a large area of the retina.

Infrared radiation was removed from the beam with a 2.5 cm pyrex cell containing distilled water. With this cell in place, intensities as high as 121 watts cm^{-2} were available at the cornea. The spectrum, calculated from published data²² and the transmission of the optical

system, is given in Figure 3. Various filters were used to select desired parts of the spectrum as shown in Figures 4 and 5; for those in Figure 4, the transmission was measured with a Beckman Model DKLA spectrophotometer; for those in Figure 5, the data were given by the supplier.²³

Xenon Flash System

In the xenon system, commercial lamps were excited by discharge of capacitors in appropriate circuits to give durations of 50 microseconds and 1 millisecond. The two lamps used were Edgerton, Germeshausen and Grier (EG&G) FX-33 and FX-42. The output and spectrum of the lamps are shown in Figures 6 and 7. The output was measured with an EG&G "Lite-Mike" and a Tektronix Model 502 oscilloscope. The "Lite-Mike" has a response time of 4.0 microseconds, a spectral response varying over the visible range with a maximum between 0.5 and 1.0 μ , and with an aperture of about 0.6 mm. The time course of the flash output is shown in Figure 6. Pulse durations are defined by $\Theta_{1/3}$, the time between 1/3 rising and falling amplitudes. The spectrum, Figure 7, is taken from various sources^{24,25,26} and shows a maximum at ~ 47 microns, a minimum at ~ 0.78 microns and further rise at longer wavelengths.

The optical and ancillary systems are shown in Figures 8 and 9. The animal was placed in a supine position, with the cornea position in an artificial pupil (5 mm), 12 mm below the surface of the flash lamp. Neutral density and spectral filters inserted between the lamp and the eye were used to control flash intensity and spectrum. A plastic contact lens electrode was positioned over the cornea and filled with saline solution during both exposure and ERG measurement.

This lens was abraded in order to diffuse transmitted light and to irradiate larger areas of the retina.

The transmission of the spectral filters is shown in Figure 10. The output after removing the infrared radiation was $4.9 \text{ joules cm}^{-2}$ for the FX-33 and $3.2 \text{ joules cm}^{-2}$ for the FX-42. For filters 1 through 5, the transmission was measured with a Beckman Model DK1A recording spectrophotometer; for filters 6 and 7, the characteristics are as given by the supplier.²⁷ To obtain flashes of varying spectral quality but of equivalent energies, the arrangements shown in Table I were used. These were obtained from the curves of "Lite-Mike" output vs. time. For peak output, the output was multiplied by the transmission of the filter and by the sensitivity of the "Lite-Mike"; for the total energy the product was integrated over the duration of the flash. These outputs were not corrected for the losses in transmission by the contact lens.

MEASUREMENT OF ERG

The optical system for measuring ERG threshold after blinding (adapting flashes) was essentially the same for the two light sources shown in Figures 2 and 8. In Figure 8, after flash blinding the eye, the flash lamp assembly was lifted out of position, the mirror (45°) and the 50 mm lens were moved into position, without moving the animal. The ERG test-light source was a Sylvania CZA projection lamp with an effective temperature of 3300°K ; there was no modification of the output spectrum. The intensity of the light at the cornea was controlled grossly, in steps, by inserting appropriate neutral density filters mounted on a wheel and for fine control, continuously, by the neutral density wedge. The duration of the pulse (35 milliseconds) was controlled by the Compur shutter. The arrangement of

the optics, the artificial pupil, the contact lens and eye are shown in Figure 11.

For use with the arc system after flash blinding, the large 45° flat mirror was moved from the arc light-path into the ERG test light-path, allowing irradiation from the ERG test lamp to impinge on the cornea; again without moving the animal.

The method of recording ERG voltages was similar to that of Dowling.⁴ Before flashing, a baseline (ERG) threshold was obtained after dark adaptation by exposing the subject's eye to successively more intense flashes of the ERG test lamp in order to determine the lowest intensity which would evoke a retinal response just noticeable above background noise. As quickly as possible after flashing (within 10-15 seconds), the threshold ERG was again obtained by adjusting the light intensity with the neutral density filters. This threshold response was obtained in succeeding trials over a period of one hour, until the eye had recovered to the pre-flashed level, or until it was obvious that further recovery would be either slow or absent.

The recovery of ERG sensitivity is expressed as the change in light intensity as determined by noting the transmission of the filters which is required to produce the threshold ERG. In curves showing recovery, the ordinate is obtained by subtracting the sum of the optical densities of the neutral density filters during recovery from the sum of optical densities of the filters before flashing.

To obtain the ERG threshold, the recording electrode was either a contact lens (xenon flash system) or the wick (arc system); the indifferent electrode was a silver-silver chloride or wick electrode, placed subcutaneously or through a wound made near the eye. These

electrodes were connected to a DC preamplifier, Tektronix Model 122, with the gain set at 1000, the low frequency response control set at 0.25 hertz and the high frequency response set at 250 hertz. The output of the preamplifier (single ended) was connected to the vertical amplifier (double ended) of a dual beam oscilloscope, Tektronix Model 502, with the sensitivity set at 50 millivolts/cm and the amplifier set for DC.

In determining ERG threshold before flash blinding, the required intensity eliciting an ERG response in rod-containing retinas is very low and presumably corresponds to scotopic vision. After flash blinding, varying somewhat with the level of background noise and receptor distributions, the intensity of the ERG test light required for the same threshold response is much higher (corresponding to photopic response for cone and/or mixed retinas). As recovery proceeds, the required light intensity is gradually reduced to the level needed before flash blinding, i.e., scotopic response. In contrast to the method in which a constant stimulus is used and the changes in response measured, use of the above procedure in which threshold is measured probably disturbs the "dark adaptation" process less, both before and after recovery from flash blinding.

The light source used for generating ERG test flash was also used for light adapting the eye by prolonged exposure to light of lower intensities. With no attenuating filters, the irradiance at the cornea was ~ 0.02 watts cm^{-2} . For long exposures, such as 15 minutes (18 joules), sufficient energy was incident on the cornea of rats to produce initial increases above the dark-adapted threshold of 6 or more log units. Lower exposures were also obtained by decreasing the outputs with additional neutral density filters.

ANIMALS

Since dark adaptation for rods and cones visual cells exposed to light is markedly different, in Table II an attempt is made to classify the retinas of animals used in these studies based on their presence on microscopic examination of the retina. For example, the rat has essentially an all rod retina and the ground squirrel all cones; the other animals have both.

Adrian²⁸ showed that the dependence of ERG response on wavelength for the rhesus monkey is similar to that of man. Blough and Shrier²⁹ also showed that the spectral sensitivity of the monkey as indicated by behavioral response is similar to that of man, except for a slightly higher sensitivity of the monkey at short wavelengths. A comparison of psychophysical adaptation curve for man in Figure 1, with adaptation curve for the rhesus monkey in Figure 12 from ERG threshold measurements, shows that the two curves are qualitatively similar. Also shown is the cone-rod break, somewhat emphasized in these log-threshold log-time plots. Thus, in structure and performance, the monkey eye is much like the human eye and its use probably affords the least risk in extrapolating animal results into expected human performance.

Animals were anesthetized with an intravenously administered solution of sodium pentobarbital, 50 mg/ml. The depth of anesthesia was adjusted so that the electrical interference from spontaneous muscular activity and eye movements was minimal. The eyelids of each animal were retracted by gently putting on two sutures placed in the outer margins of each eyelid. Except for the albino rat, the pupils of all animals were dilated with several drops of a 1 per cent solution of atropine sulfate. To prevent hypothermia, the animals were kept warm, as needed, with either a blanket or a heating pad.

RESULTS

This study was designed to show in several species 1) the effects of high intensity flashes on recovery of visual sensitivity, 2) the relationship between total energy and the rate (power) at which light was delivered, 3) the influence of pulse duration and 4) the spectral sensitivity of the eye to blinding flashes of different wavelengths. The first two groups of experiments were performed with "white light", i.e., the output of the arc, except that filtered by the water cell, or the output of the xenon flash system with the infrared filter.

A typical curve, summarizing the effect of varying flash duration on recovery of albino rats exposed to 10, 100 and 1000 millisecond flashes, is presented in Figure 13. For these conditions, the earliest measured increase in ERG threshold varied from approximately 4 to 6 log units with the highest threshold rise obtained at the highest energy, 1.2 joules/cm². Recovery was most rapid for the first 50 to 100 seconds, then a slowing with essentially a plateau for up to 1000 seconds, and then a further slow recovery. Recovery was complete or nearly so in 3 to 4 days. The time for complete recovery was perhaps slightly longer for exposures at the higher energy level. In these and subsequent plots, N refers to the number of eyes tested, i.e., the curve represents the average response for N samples.

I. Effects of Flash Blindness in Different Species

The differences in response among various species exposed to 10 millisecond flashes of the same energy, 1.2 joules cm⁻², are evident from the data summarized in Figure 14. At the two extremes are the slow recovery for the albino rat (with a curve similar to that in Figure 13), and rapid recovery for the ground squirrel. The

difference between these two curves is striking and it undoubtedly represents the difference in adaptation for rods (rat) and cones (ground squirrel). At 30 seconds recovery time, the threshold increase is only 1 log unit for the squirrel as compared to 5 log units for the rat. Recovery is essentially complete for the ground squirrel within 5 minutes, but not with the rat, even after one hour.

The other animal species studied showed intermediate responses, e.g., the curve for the squirrel monkey approached within 1 log unit that of the rat, whereas the curve for the chicken was very similar to that for the ground squirrel and presumably also due to cone adaptation.

The cat is intermediate in recovery, slower than the ground squirrel but more rapid than the squirrel monkey. Results, based on 3 cats and 2 kittens, indicate that the threshold rise initially and during recovery for the kitten is about one log unit higher than for the cat, suggesting that in this species, age may influence the retinal rod-cone distribution.

II. The Effect of Flash Duration, Power and Energy

A. Albino Rat

The effect of 1 millisecond flashes of light at increasing intensity, with energies varying from 0.006 to 0.121 joules cm^{-2} , is shown in Figure 15. There was a progressive increase in the threshold both initially as well as during recovery. For the sake of comparison, the recovery after prolonged light adaptation is also presented. The rise in threshold initially and during dark adaptation is higher for eyes that are light-adapted continuously for 15 minutes than for eyes exposed to 1 millisecond flashes. In another experiment with a 2

second flash at $242 \text{ joules cm}^{-2}$, the rise in threshold was slightly higher (almost 7 log units), than after prolonged light adaptation, with very little recovery after 48 hours.

In Figure 16 a smaller amount of energy, $1.2 \text{ joules cm}^{-2}$, was delivered in each instance, but at different rates, that is, in 10, 100 and 1000 milliseconds. The resultant curves were nearly the same, generally within $1/4$ log units, for all three exposures. Thus, there was no definite trend between the threshold rise, both initially as well as during recovery, and the power of the flash. This indicates that for a given amount of total energy, the rate at which it was delivered, at least within the range of exposure times indicated, had little effect on the rise in threshold early in the recovery. Other experiments indicate that this may not be the case when considering the time for essentially complete recovery.

B. Ground Squirrel

The results for pulses of various durations at the same power, 81 watts cm^{-2} , are given in Figure 17. As already indicated, the shape and slope of the curves for the ground squirrel differ considerably from those for the rat, although as in the rat, there was a fairly progressive increase in threshold and in recovery time with increasing duration of the pulse. For curves in Figure 18, flashes of the same energy, $1.2 \text{ joules cm}^{-2}$, were delivered in 10, 100 and 1000 milliseconds and were found, as with the rat, to produce nearly equivalent responses.

C. Rhesus Monkey

In Figure 19 is shown the recovery of monkeys exposed to pulses of different duration, 50 μ seconds and 1 millisecond, but containing

nearly the same energy, 0.34 and 0.29 joules cm^{-2} . This result also suggests that total energy and not the rate of delivery is the most important factor affecting the threshold. These data extend the range of flash duration where this relationship is valid, from 1 millisecond down to 50 $\mu\text{seconds}$.

D. Summary of the Effects of Total Energy on ERG Threshold

The extent of flash blindness increases as the energy incident on the cornea increases, whether this involves longer durations at the same power or increased power at the same pulse duration.

As measured by the increase in log threshold, flash blindness seems to depend on the energy and not on the power or pulse duration. As measured by the time required for apparently complete recovery, there is some indication that it may depend on the rate.

In Figures 20 and 21, the increase in threshold in rat, ground squirrel and monkey 30 seconds and 60 minutes after flash is plotted as a function of the incident energy. The curves for prolonged exposure to steady light are included for rat and monkey and are nearly linear. The slope for the 30 second recovery is ~ 1.0 . Over a wide range of flash energies, the curve for prolonged exposure has a slope which is higher than all of the short flash curves. For this case, then, the increase in ERG threshold is about proportional to the first power of the incident energy. For short pulses, for energies greater than 0.1 joules cm^{-2} , the slope is much lower. In some cases, the slope of the curves are higher at lower energies, and this would probably be the case for all the curves that are nearly horizontal at higher energies if the exposures were extended to even lower energy levels. The curves for 10 minutes recovery are intermediate.

Under these exposure conditions the increase in threshold becomes disproportionately smaller as flash energy is increased, varying as the $1/2$ or as slowly as the $1/4$ power. To raise the threshold of the rat more than 4 log units at 30 seconds recovery, more than 3 log units at 10 minutes recovery, or more than 2.2 log units at 60 minutes recovery, large increases in energy are needed. It is difficult to state the parameters of flash blindness more definitely without knowing the relation between the increase in ERG threshold and loss of visual acuity. Results with the ground squirrel strongly suggest flash blindness of 10 to 15 minutes for the photopic (cone) phase of adaptation, cannot be produced without increasing the incident energy to levels that may produce permanent injury.

III. Effect of Spectral Quality

Exposures for the rat, ground squirrel and kitten were obtained with the carbon arc and filters as shown in Figures 3 and 4, and for the monkey with the xenon flash system and the filters in Figures 7 and 10. The filters are designated by the wavelength of peak transmission.

A. Rat

Figure 22 shows the recovery of the albino rat after exposure to 10 millisecond flashes at $8.3 \text{ watts cm}^{-2}$ ($0.083 \text{ joules cm}^{-2}$). There was very little rise in threshold for the spectral bands at 0.665 and 0.734μ . Bands at 0.486 and 0.556μ all had about as much effect as "white light"; the 0.556μ band was possibly somewhat more effective. Similar results were also obtained at $16.5 \text{ watts cm}^{-2}$ with a somewhat smaller difference between the effects of "white light" and the bands at 0.41 and 0.56μ .

For the Long Evans rat with pigmented iris and retina, recovery from 0.665 μ and 0.734 μ flashes was slower than for the albino rat, whereas recovery from 0.486 μ and 0.556 μ flashes was about the same as for the albino rat.

B. Ground Squirrel

Recovery from 2 second flashes at energies of 16.6 joules cm^{-2} is shown in Figure 23. The threshold raising effect is greatest for "white light" and for the 0.556 μ band with possibly a slightly greater effect for the latter, less effect for the 0.486 μ and 0.665 μ and very little effect for the band at 0.734 μ .

C. Kittens

With kittens, the response to flashes of different spectral bands was similar to the results seen with the albino rat and ground squirrel. At 30 seconds recovery for the 1 second flashes at energies of 0.83 joules cm^{-2} , the threshold rise was greater for two bands at 0.485 μ , 0.556 μ and for "white light" than for the bands at 0.665 μ and 0.734 μ .

D. Rhesus Monkeys

The experiments with the rhesus monkey were conducted with narrower bands of the spectrum.

The results for 50 μ second flashes with energies of 0.03 joules cm^{-2} are shown in Figure 24. Two groups of curves are evident, those at 0.33, 0.65 and 0.74 μ bands which have little effect, and those bands at 0.46, 0.52 and 0.61 μ , with larger and similar effects for "white light". Among the latter group, the effect was somewhat greater for the 0.46 μ and the 0.52 μ bands and slightly smaller for the 0.61 μ band and the "white light".

Results for flashes of greater energy, $0.25 \text{ joules cm}^{-2}$, delivered in 1 millisecond, Figure 25, show similar response curves as those in Figure 24, except for a somewhat higher rise in threshold during the first several minutes of recovery. Final recovery time was also somewhat longer with the 1 millisecond flashes. The 0.46μ band was slightly lower than the 0.52μ and the 0.61μ bands, both of which were equally effective as "white light". However, differences between the curves for 0.46 to 0.61 exposures (as with $50 \mu\text{second}$ flashes mentioned above) are probably within experimental error.

Very small response to the 0.33μ band might be attributed to low transmittance of the contact lens but measurements made after drilling a hole in the center of the lens gave no higher ERG voltages. The lack of effect of this short wavelength is due to low transmission of the eye. Spectral bands in the visible and up to 0.75μ are probably transmitted to the retina with little attenuation and the very small response at these long wavelengths must be attributed to lack of response of the rod and cone receptors.

E. Summary

For all the species studied which include animals with mixed retinas as well as animals with retinas with a predominance of either cones or rods, wavelengths in the range of 0.46 to 0.61μ were the most effective in raising the ERG threshold and increasing recovery time, and from this evidence, very likely most effective in producing flash blindness. Over the rest of the range of the sensitivity of the eye, the lack of response must be ascribed to either the insensitivity of visual reception in the retina, e.g., to the longer wavelengths, or the inability of the light to reach the retina. Within

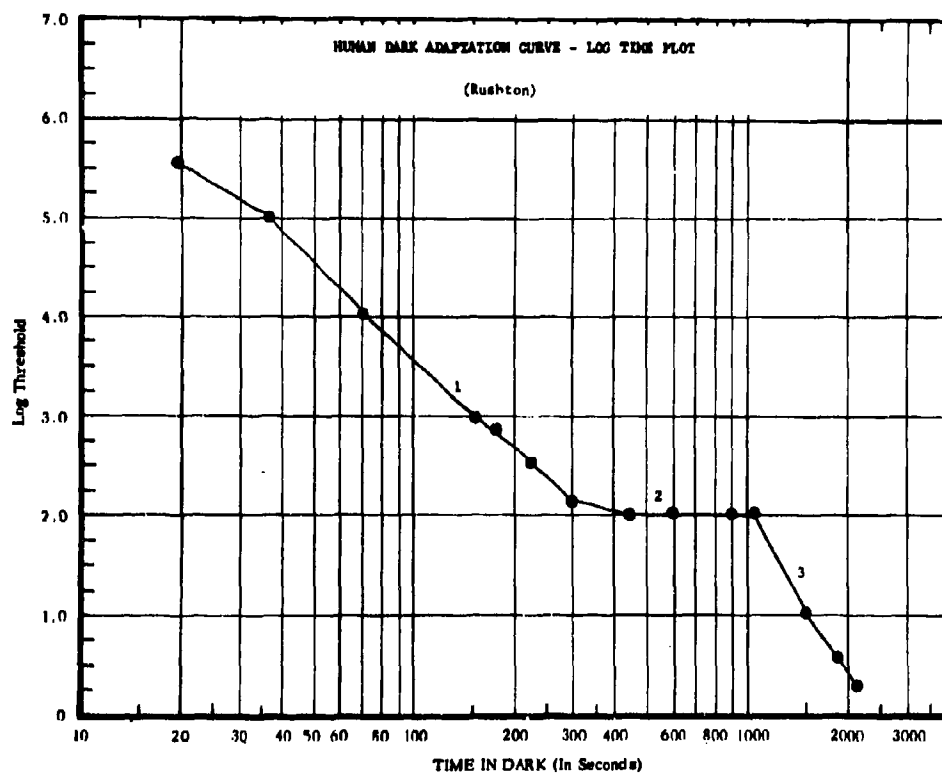
the limits imposed by the relatively wide bands used in these flash experiments, it seems that the dependence of flash blinding potential on wavelength is very similar to the wavelength maximum for visual pigments of the retina and corresponds to the region of greatest spectral sensitivity of the eye for vision.

These and additional results are discussed elsewhere^{19,20}.

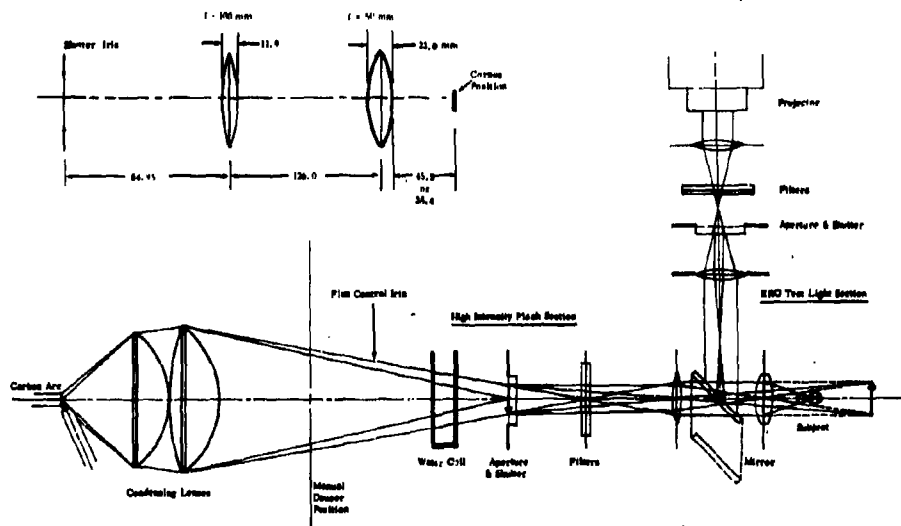
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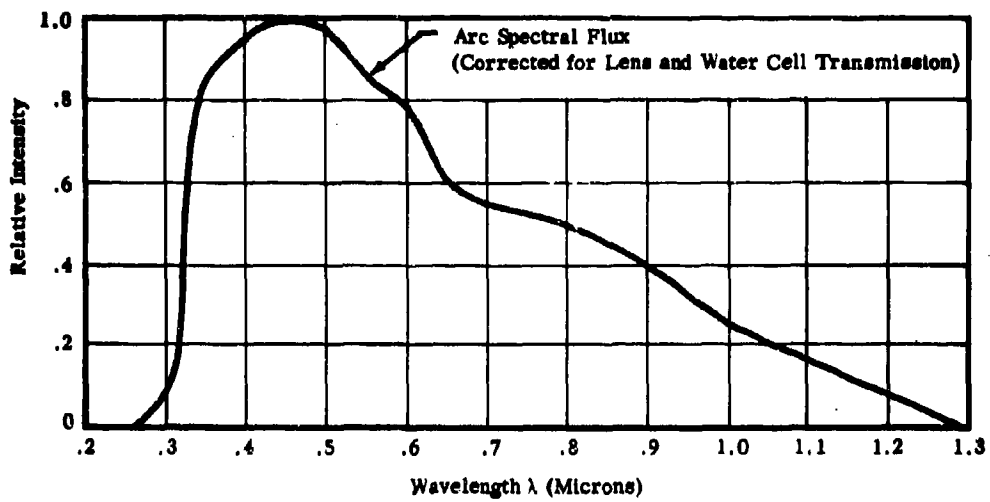


1. Human dark adaptation curve - log time plot (Rushton).



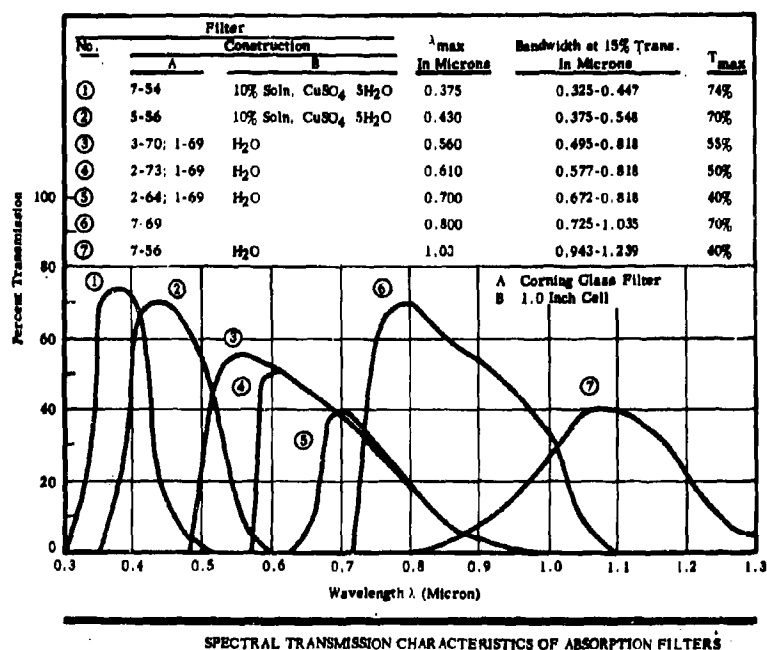
CARBON ARC FLASH AND ERG APPARATUS

2. Carbon arc flash and ERG apparatus.

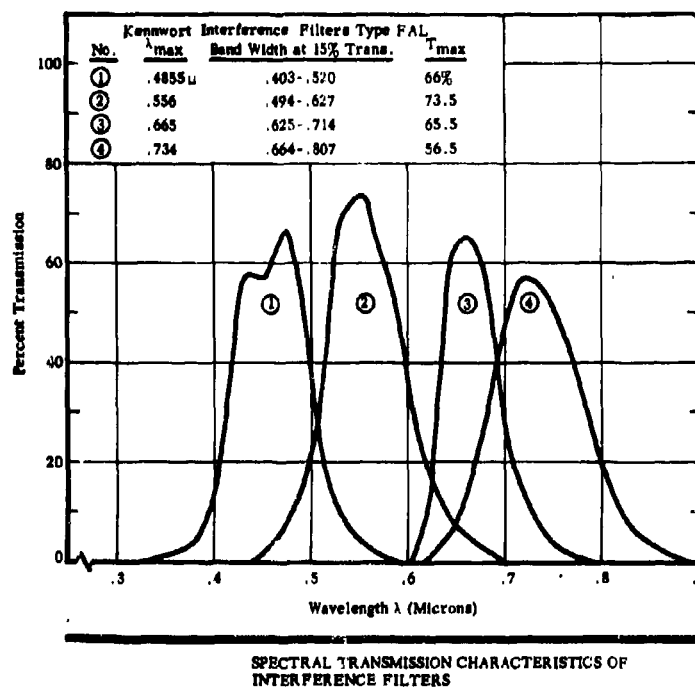


SPECTRAL FLUX INTENSITY OF CARBON ARC

3. Spectral flux intensity of carbon arc.

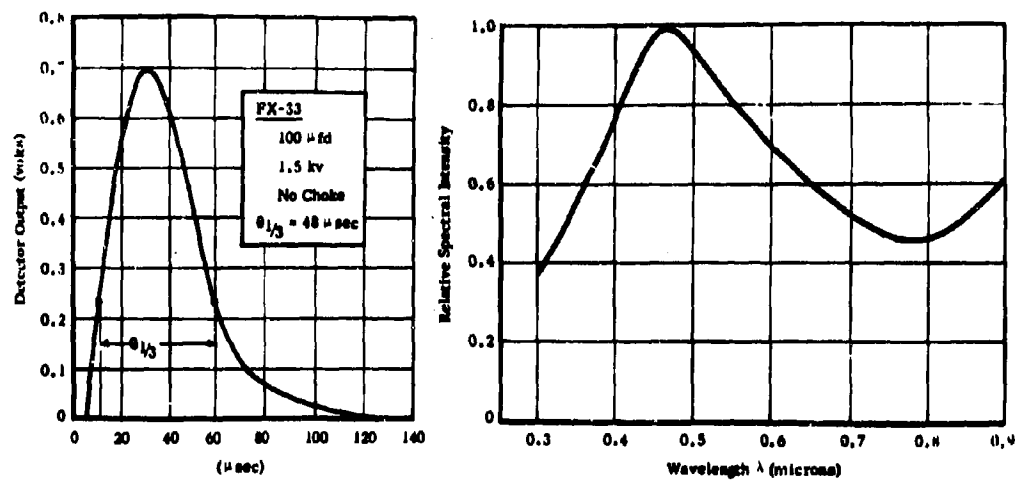


4. Spectral transmission characteristics of absorption filters.

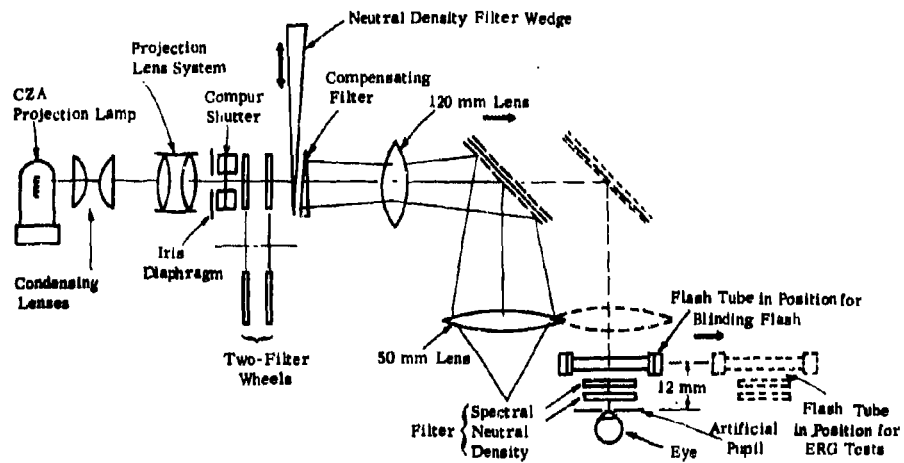


5. Spectral transmission characteristics of interference filters.

TYPICAL FLASH CHARACTERISTICS OF XENON LAMP

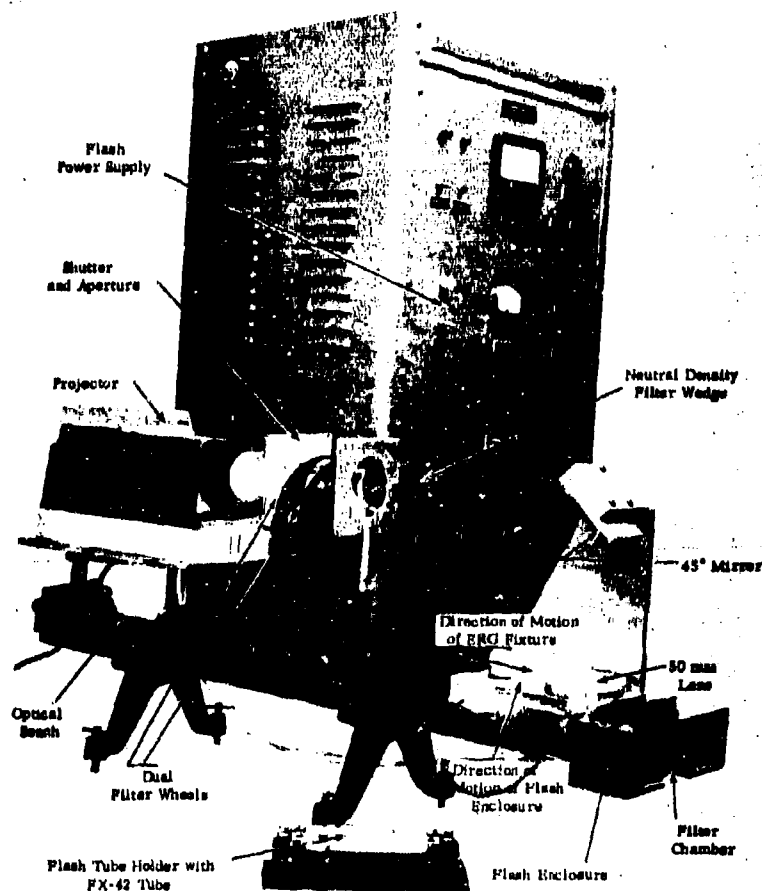


6. Typical flash characteristics of xenon lamp.
- 7.



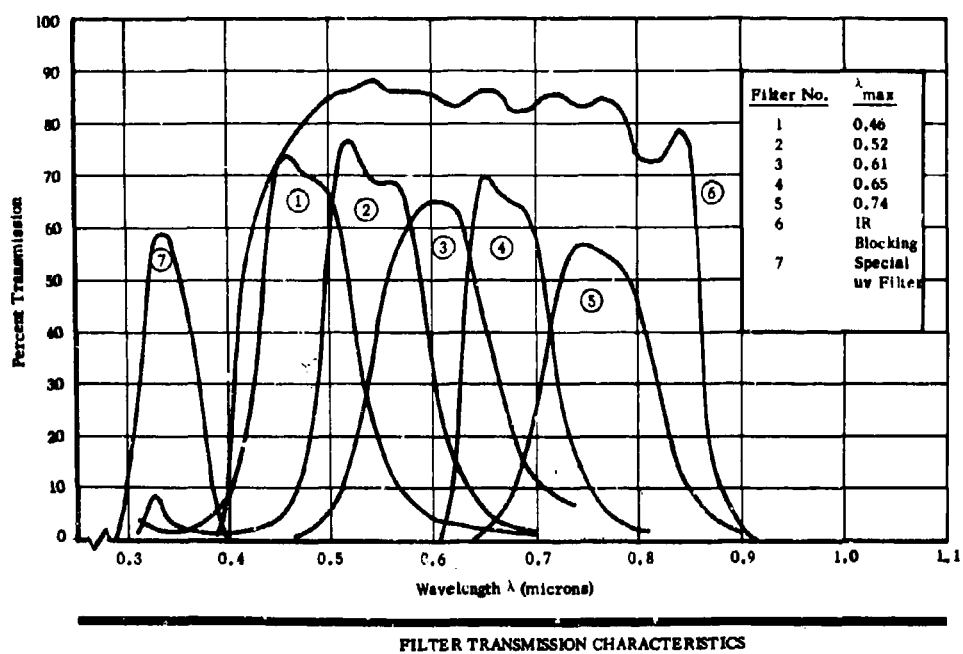
SCHEMATIC OF SHORT-DURATION, HIGH-INTENSITY FLASH AND ERG APPARATUS

8. Schematic of short-duration, high-intensity flash and ERG apparatus.

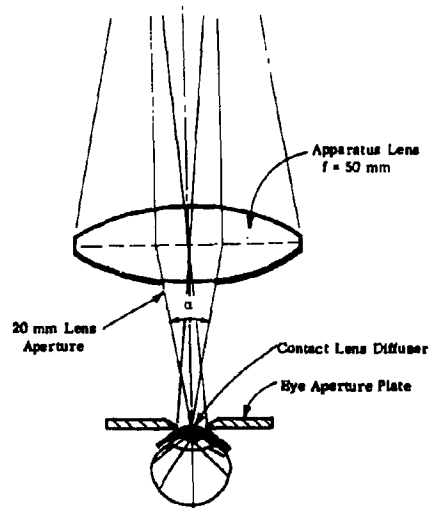


HIGH INTENSITY FLASH AND ERG TEST LIGHT APPARATUS

9. High intensity flash and ERG test light apparatus.



10. Filter transmission characteristics.

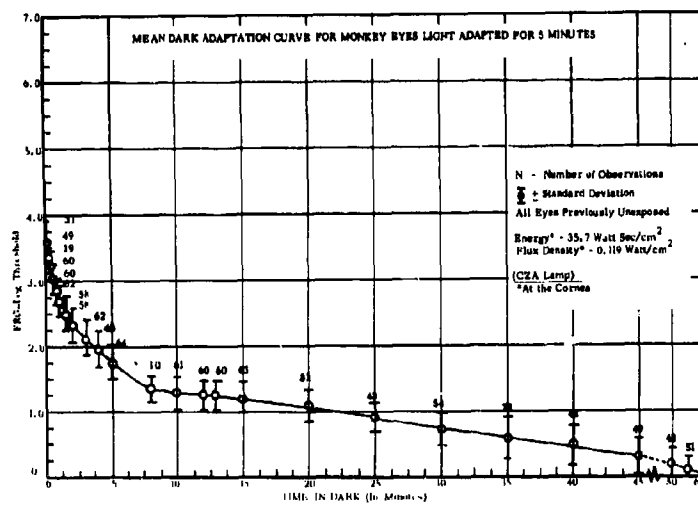
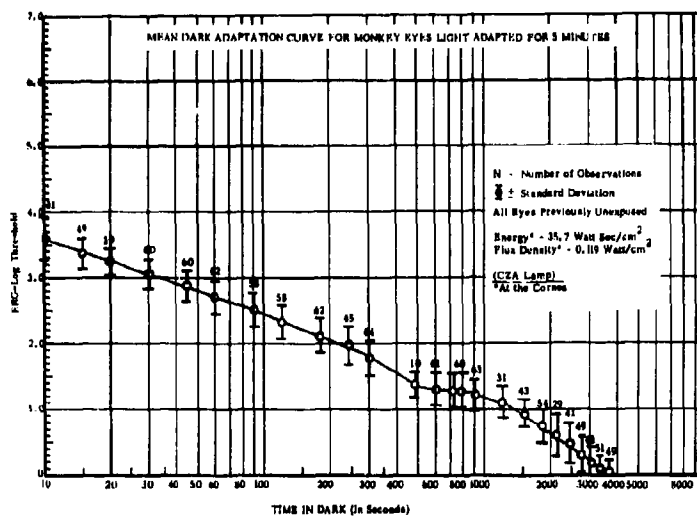


Artificial Pupil Dimensions

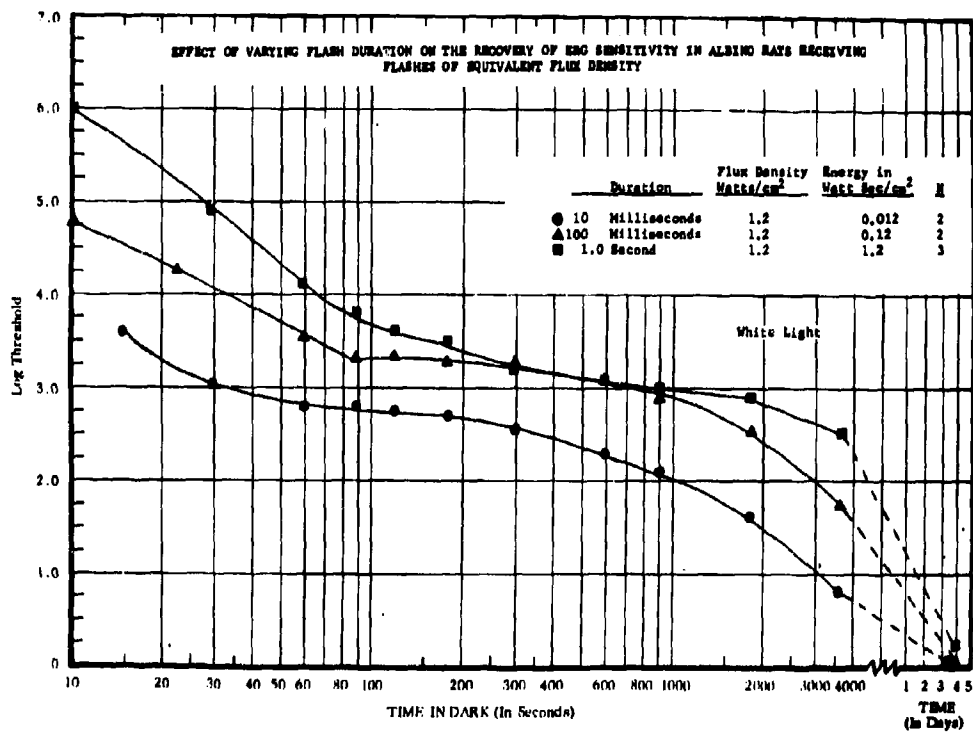
Nominal Diameter	Measured Diameter	Area	α
mm	mm	cm ²	
5	4.98	0.195	35
3	2.92	0.0669	32
2	1.98	0.0308	31

ARTIFICIAL PUPIL DIMENSIONS AND ENTRANT ANGLES
FOR ERG FLASHES

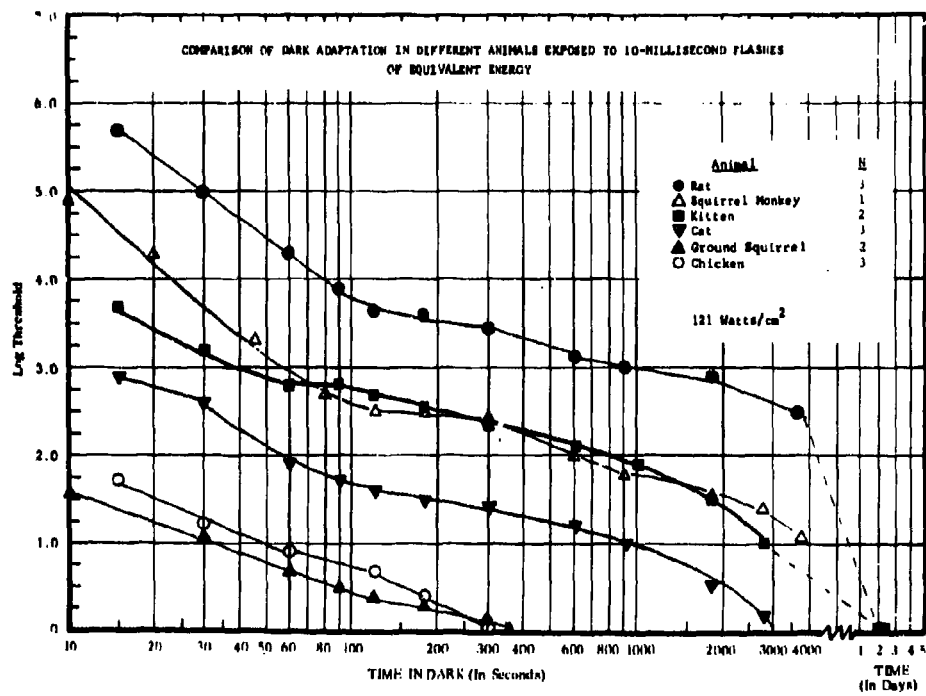
11. Artificial pupil dimensions and entrant angles for ERG flashes.



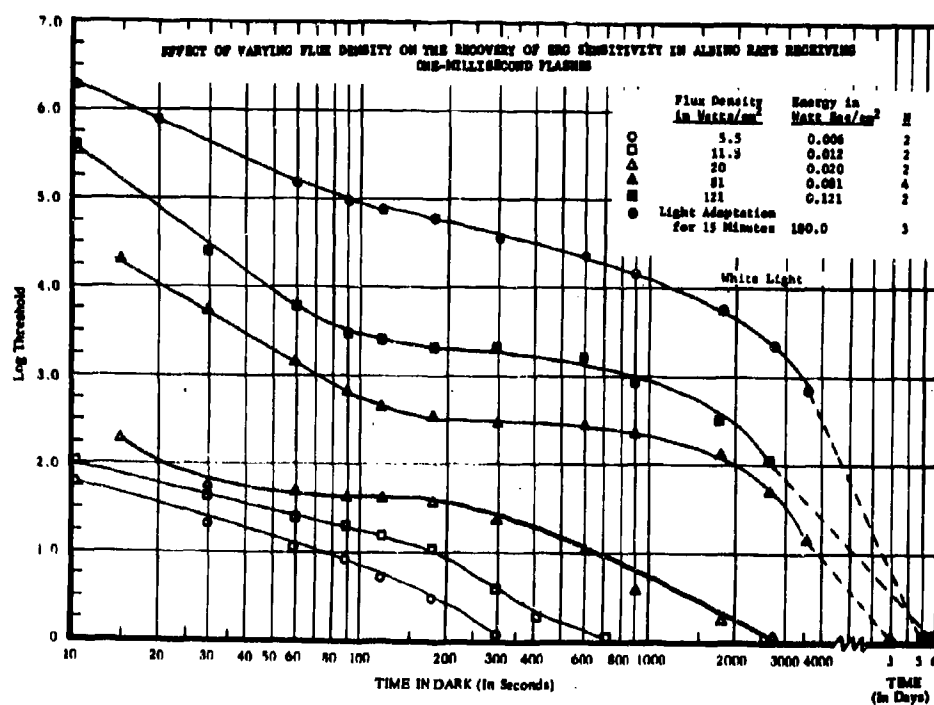
12. Mean dark adaptation curve for monkey eyes light adapted for 5 minutes.



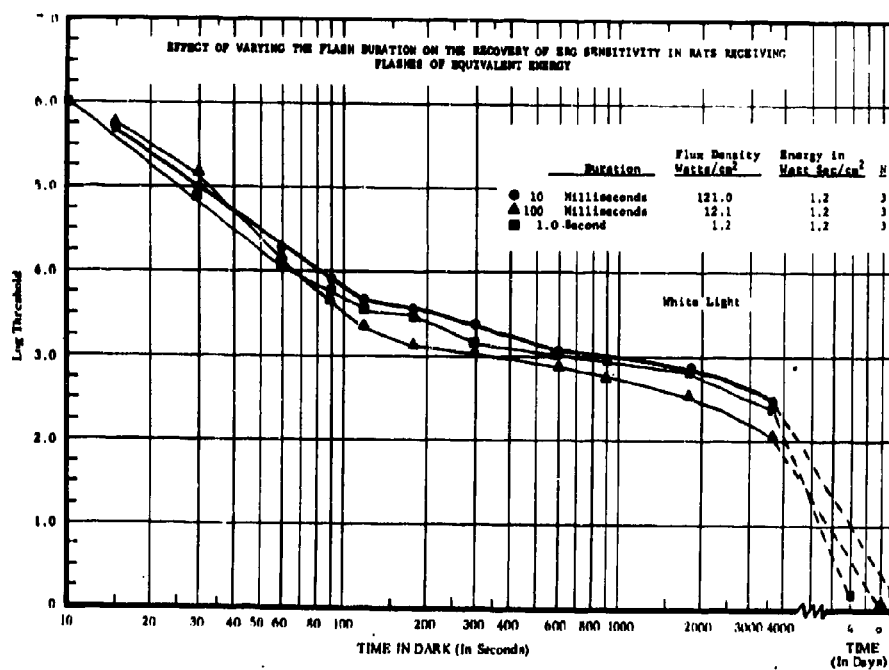
13. Effect of varying flash duration on the recovery of ERG sensitivity in albino rats receiving flashes of equivalent flux density.



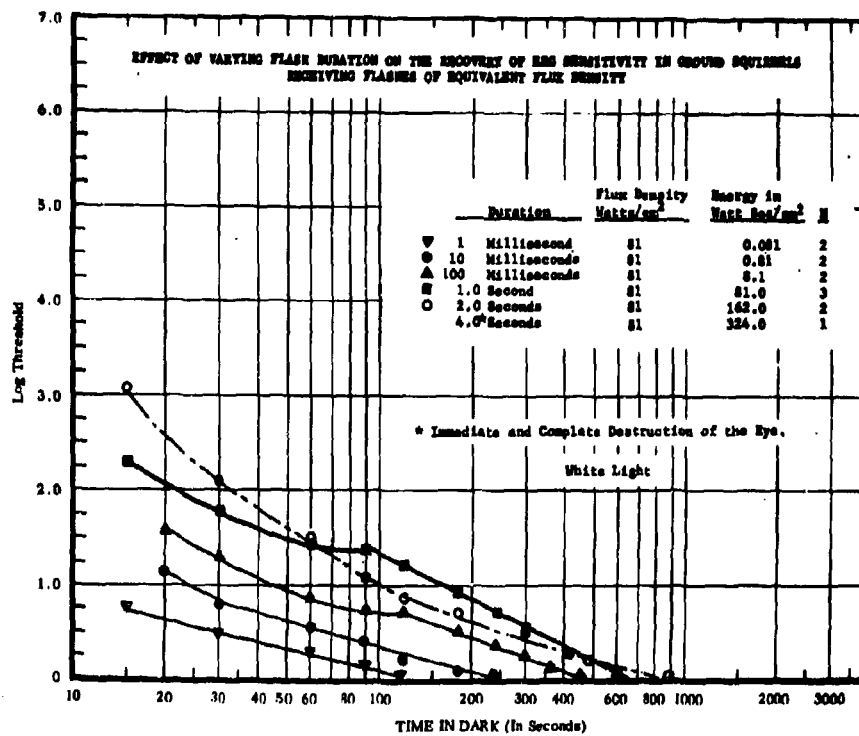
14. Comparison of dark adaptation in different animals exposed to 10-millisecond flashes of equivalent energy.



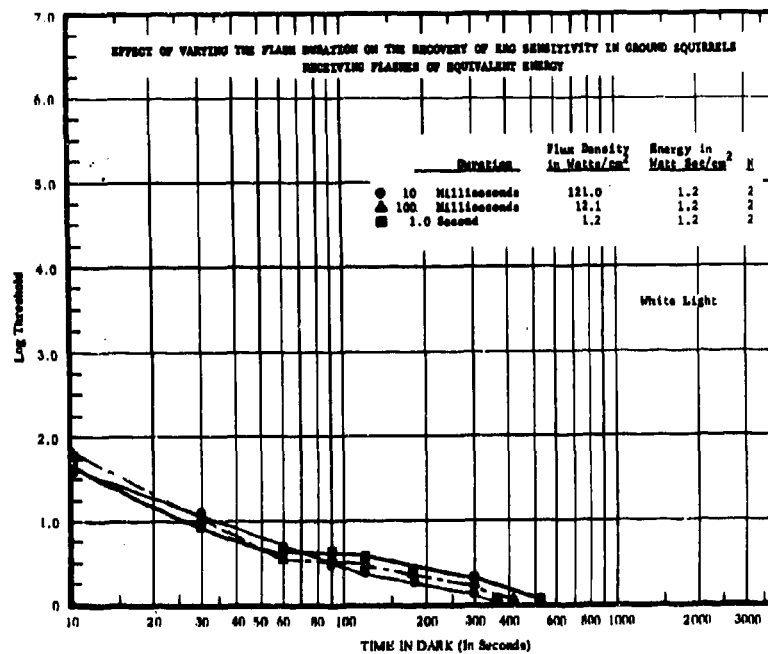
15. Effect of varying flux density on the recovery of ERG sensitivity in albino rats receiving one-millisecond flashes.



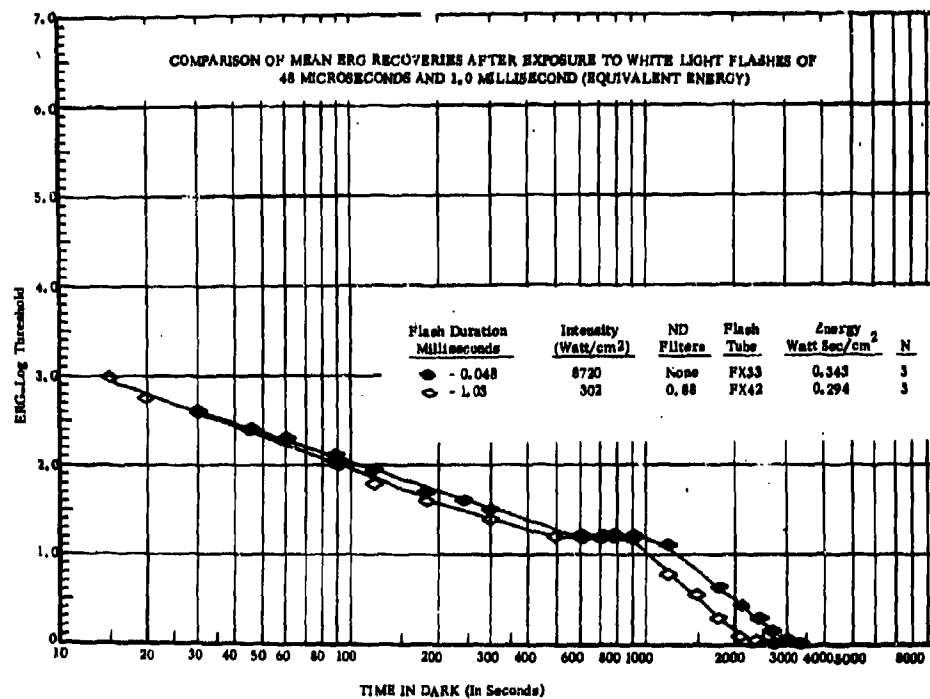
16. Effect of varying the flash duration on the recovery of ERG sensitivity in rats receiving flashes of equivalent energy.



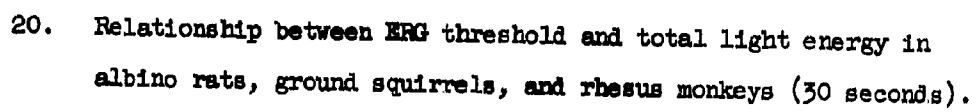
17. Effect of varying flash duration on the recovery of ERG sensitivity in ground squirrels receiving flashes of equivalent flux density.

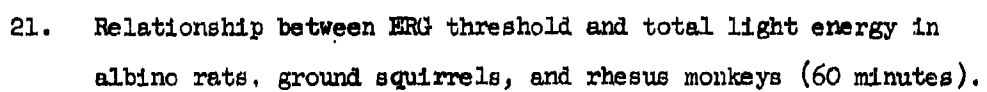


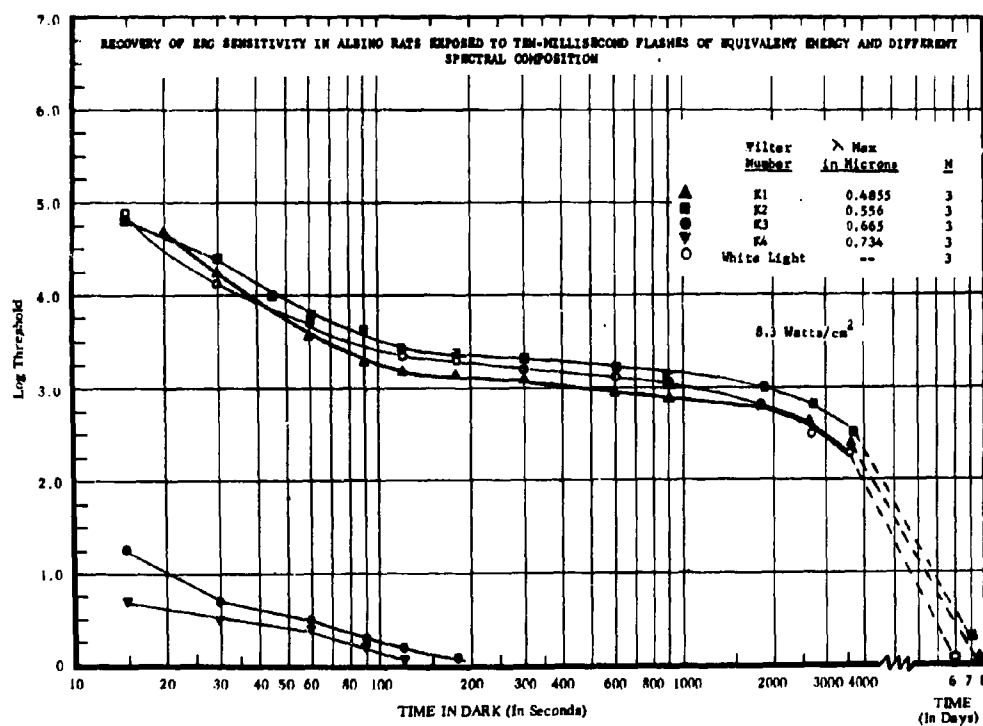
18. Effect of varying the flash duration on the recovery of ERG sensitivity in ground squirrels receiving flashes of equivalent energy.



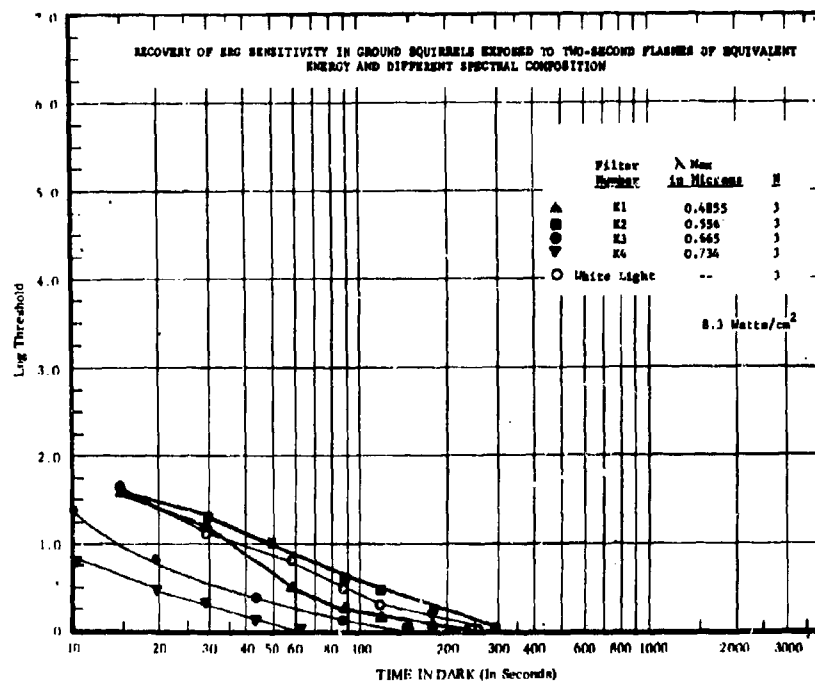
19. Comparison of mean ERG recoveries after exposure to white light flashes of 48 microseconds and 1.0 millisecond (equivalent energy).



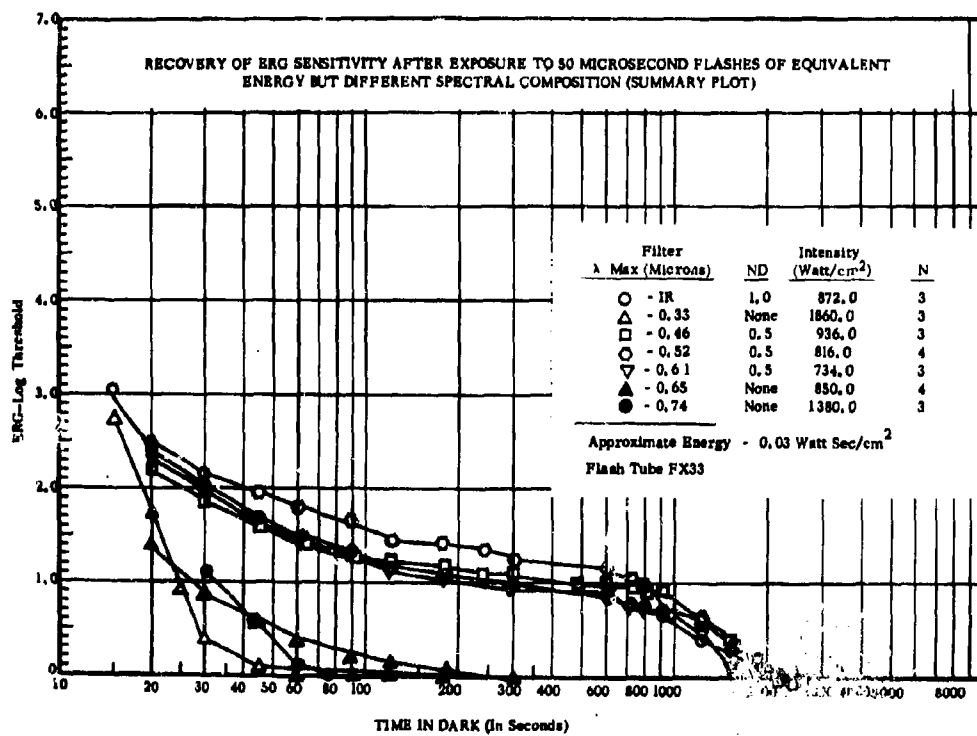




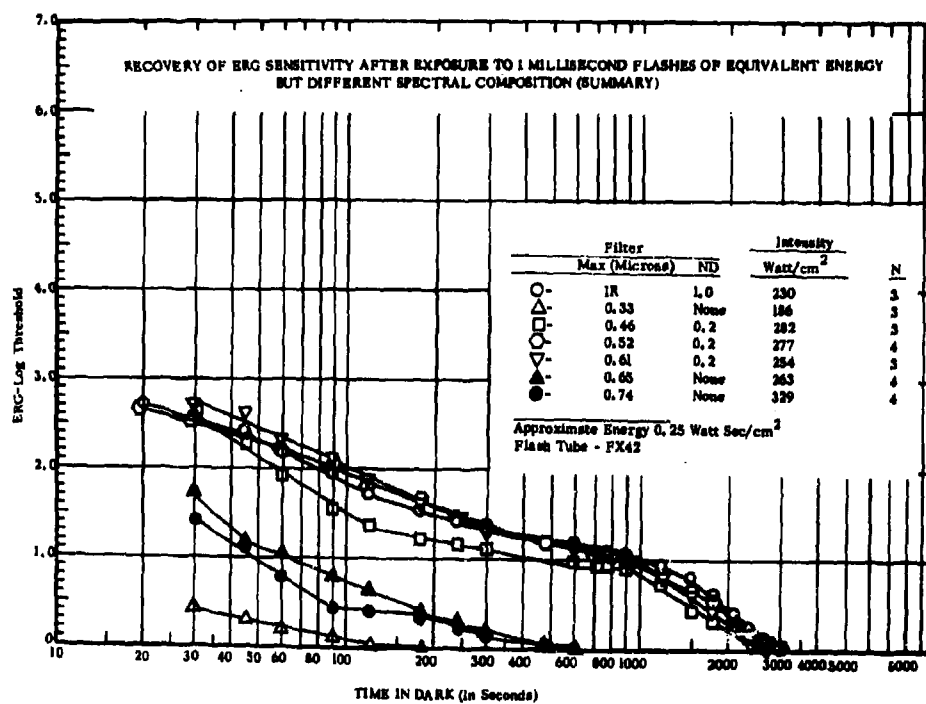
22. Recovery of ERG sensitivity in albino rats exposed to ten-millisecond flashes of equivalent energy and different spectral composition.



23. Recovery of ERG sensitivity in ground squirrels exposed to two-second flashes of equivalent energy and different spectral composition.



24. Recovery of ERG sensitivity after exposure to 50 microsecond flashes of equivalent energy but different spectral composition (summary plot).



25. Recovery of ERG sensitivity after exposure to 1 millisecond flashes of equivalent energy but different spectral composition (summary).

Sam P. Battista

TABLE I. ARRANGEMENT FOR EQUIVALENT ENERGY
FLASHES OF DIFFERENT SPECTRAL QUALITY

<u>Flash Tube</u>	<u>Spectral Filter</u>	<u>Neutral Density Filter</u>	<u>Energy at Artificial Pupil joules cm⁻²</u>	<u>Neutral Density Filter</u>	<u>Energy at Artificial Pupil joules cm⁻²</u>
FX-33	IR	1.0	.049	.5	.15
	.33	None	.13	-	--
	.46	.5	.048	None	.16
	.52	.5	.042	None	.14
	.61	.5	.036	None	.12
	.65	None	.051	-	--
	.74	None	.047	-	--
FX-42	IR	1.0	.32	.7	.64
	.33	None	.27	-	--
	.46	.2	.37	None	.59
	.52	.2	.40	None	.64
	.61	.2	.36	None	.55
	.65	None	.34	-	--
	.74	None	.44	-	--

Sam P. Battista

TABLE II. CHARACTERISTICS OF ANIMALS

<u>Animal</u>		<u>Predominant Visual Cells</u>
1) Albino rat	Rattus norvegicus	rod(a)
2) Long Evans rat	Rattus norvegicus	rod*
3) Squirrel monkey	Salimiri sciurea	rod†
4) Cat	Felis catis	mixed (rod > cones)(b)
5) Chicken	Gallus domesticus	cone(c)
6) Ground squirrel	Citellus mexicanus	cone(d)
7) Monkey	Macaca mulatta	mixed(e)

* Assume to be like other rats--predominantly rod visual cells

† Based on dark adaptation curves from these studies

(a) Walls, G. J. Comp. Psychol. 1934, 18, 363.

(b) Schultz, M. Arch. Mikr. Anat. 1866, 2, 175.
Adrian, E. D. J. Physiol. 1946, 105, 24.

(c) Wald, G. Nature, 1937 b, 140, 545.

(d) Vaidya, P. G. J. Comp. Neurol. 1964, 122, 347.

(e) Adrian, E. D. J. Physiol. 1946, 105, 24.
Dowling, J. Science, 1965, 147, 57.

PANEL DISCUSSION

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Panel Discussion

Dr. Glenn A. Fry

First of all, I would like to express our appreciation to the staff here at Natick Laboratories for arranging this symposium on flash blindness. The panel this morning will attempt to summarize some of the major contributions of the papers and discussions held yesterday. We hope at the same time each of you will consider it an opportunity to either raise questions or to make comments. Although we had the opportunity for asking questions yesterday, I am sure that after we put all of our thoughts together there will be some questions that need further discussion. We have divided the program this morning into topics giving each of the members of the panel a few things to say. Finally, I will attempt to summarize some of the contributions to the conference. First of all, I'm going to call on Dr. Dzendolet to discuss a problem in which he has a special interest, that is, the use of units in the study and description of flash blindness, and to make what other comments he desires.

Dr. Ernest Dzendolet

Before starting the topic of the use of units, I'd like to talk about psychophysical methods in general, and as used in yesterday's presentations. In the papers that were presented, as is usually the case at conferences and meetings, there was not much time devoted to descriptions of the psychophysical methods. If one investigator doesn't clearly define the psychophysical method which he uses, it is very difficult for someone else to confirm his findings. In addition, there is the problem of differences in the observed thresholds as a result of using different psychophysical methods. Generally,

I think that in adaptation experiments probably the most useful technique is the use of only an ascending series in the method of limits, that is, where the stimulus is presented in some sort of increasing quantity to the subject. Now, within this method you have your choice of either a discrete, or a continuous manner of stimulus presentation. I think a continuous manner is more desirable simply because you usually have available a neutral density wedge which can be turned to some known value or position. If the subject himself has control of this wedge movement, there is the possibility that you will get variations between subjects. This results from differences in their rates of movement. A modification of this method would be the use of a motor-driven wedge. In this procedure, the subject presses a button until the wedge reaches the desired position, that is, until he sees the stimulus, then he releases the button, stopping the wedge, and you take a reading. In some cases you will want to have a reversing switch so that the subject can track the stimulus. Tracking has some advantage, of course, in that the subject may overshoot. As soon as he overshoots he will become light-adapted to some degree. These are some of the problems and considerations of the experimenter, and his choice of a particular method will depend upon the type of study, and the questions to be answered by it.

In animal experiments, where physiological measures are taken, as for example, the ERG, you usually present a flash at some discrete level. I think it would be more advantageous if, instead of using a visual criterion of when an ERG appeared, a procedure of taking pictures of the oscilloscope face were used. Often, whether the experimenter realizes it or not, there is some experimental bias.

Thus, he may very well believe that a stimulus was present when perhaps there wasn't one. There are some classical examples of this case in the literature. If a method of limits using only the ascending series with discrete flashes, were presented to the preparation, and photos were taken of the response, you could then use an unbiased observer to view the photos and to judge the occurrence or non-occurrence of the ERG. The initial presence of the ERG could then be plotted as a function of the variation of the stimulus. I would recommend that those who are interested in a further investigation of other psychophysical methods which could be used, as well as their application to human and animal studies, read Woodworth and Schlosberg's "Experimental Psychology", because this book has an extensive discussion of the procedures.

I am, of course, making the assumption that there is such a thing as a threshold. Those of you who are acquainted with signal detection theory know that currently there is a debate as to whether or not a threshold actually exists. The human response to a stimulus is, in their terms, defined both by what the sensory system is doing and by some internal criterion that the subject is acting on. I think that for purposes of investigating the visual system as we are now doing, the idea that there is a threshold which varies somewhat between subjects, but which isn't influenced too much by certain other factors, is a valid concept with which to work. This is all I have to say now about psychophysical techniques or methods.

Dr. Jones

I would like to make a comment relative to your discussion of the method of limits, particularly the use of an ascending only series. Even if we assume that the subject does not overshoot his

threshold, thereby causing him to become light adapted, there is sub-threshold energy which enters the eye, thus causing some change in adaptation. The photochemical events that go on when quanta are absorbed go on whether the light is at threshold or below it. By using the ascending only series, radiant energy may still get into the eye and consequently this may affect the adaptation curve. Generally I agree with you, however, I did disagree with the idea that because the light is not visible it has no effect on events at the retinal level.

Dr. Dzendolet

Yes, what you say is quite correct; the point I was attempting to make was that the ascending only variation of the method of limits is preferred to the descending series in which you start at much higher intensities and go down to a level which cannot be seen by the subject. To avoid the problem of adaptation which results from sub-threshold energy exposures, the method of constant stimuli can be used. In this case, you merely present a discrete flash. However, this particular procedure is very time consuming, especially if you want to investigate the time course of phenomena such as dark adaptation. I think the time involved in using constant stimuli would be considerably more than in the ascending series method. Thank you very much for pointing out that there is an effect at sub-threshold energy exposures. It's a question of minimizing these effects that we are concerned with.

Major Pitts

I think we should clarify a point made earlier. You talked about electrophysiological records and gave as an example, the

electroretinogram and further, that you would like to have these records included in a presentation or paper. Now, by this, do you mean to include all of them or just a representative sample, because if you include all the records, then all you're going to have is a paper composed almost entirely of pictures.

Dr. Dzendolet

I didn't mean to imply that at all; I merely meant that if you take pictures of the scope trace at different stimulus levels, then give all the pictures to your assistant, who supposedly is an unbiased observer, and say: "Pick out in which picture there is a just discernible ERG." Then, you note the stimulus level that coincided with his evaluation of the presence of the ERG, and use that as your threshold.

Major Pitts

This is actually what most of us do. This is what I've done in the past using photographic methods. Now we use a computer and take the amplitude, change it to a time conversion, open up the gate of the computer for the length of time relative to the amplitude and put in so many counts that we don't need to take any photographic data now.

Dr. Dzendolet

Well I think some mention of the exact procedures used is important to let the reader know that you aren't just skimming the data. This, I think, adds a bit more weight to the results. I am sure that in the past there have been a number of papers in which the techniques weren't specified in enough detail. If the results

are different from those of other investigators, you don't know whether this is due to a real phenomenon, or whether it's a result of differences in the actual techniques used.

Dr. Hill

The flash blindness produced by nuclear weapons and other sources is an important applied problem. Therefore, to obtain meaningful data which can be used to solve this problem, the applied situation must be kept in mind. Analyses of such situations have shown that the course of flash blindness must be determined for the first few seconds following the exposure to the blinding source. Time is the critical factor and it is a matter of very few seconds. Under these conditions you cannot use the constant method, and I am fairly certain that you cannot use the method of limits either. I know of no one who has used either of these methods in this particular situation. In my own work, I have had to use a constantly illuminated test target, an acuity grating, which is presented along with the adapting flash and then occluded when its orientation is perceived. The times required for this perception are the data from which the thresholds are computed. These experimental conditions are similar to the typical applied situation where the target is there and at some luminance. You either see it in time or you don't. I believe that it is quite necessary for this particular problem to simulate the applied situation, but not necessarily the particular target. It would be helpful if all those in the business of flash blindness could agree on a specific target to use. In my own case, I always use an acuity grating which is an extremely generalizable target and can be calibrated against an altimeter, a reading chart, or whatever

the applied situation requires. These calibrations then allow you to predict what your visual capabilities would be in a flash blindness situation.

The problems of experimental technique in flash blindness are extremely difficult since you only have a matter of seconds in which to find the threshold. It is not a question of what happens 2 hours later, or even 15 minutes later. The operational situation is what is going to happen in the next 5 seconds. This is also the situation as far as automobiles are concerned. You're not worrying about what's going to happen about 5 miles down the road, you're worrying about what's going to happen as you go through an intersection you are now approaching.

Dr. Fry

When you mention grating, do you mean an acuity grating of a specific spacing or overall size?

Dr. Hill

No, just visual acuity gratings, i.e., black and white lines which are very easily replicated in one lab or another. They give you a standard measure of visual acuity and a standardizable type of target.

Dr. Sperling

I think the important thing is not so much which target to use but to emphasize Dr. Hill's statement that there should be a standard criterion upon which all this work is based. I happen to agree that the grating is the most versatile target.

Dr. Dzendolet

Well, let's go on to some discussion of units. First of all, let me apologize for the low level at which I will discuss them. I am sure that for many of you this is very elementary, but perhaps if we start at this level, it will be easier for all of us to go on to more complicated situations. In the June 1967 issue of the Journal of the Optical Society of America, the Board of Directors of the Optical Society suggested a number of terms for standardizing the nomenclature and symbols used in radiometry and photometry. Obviously, there is a great need to be consistent in terminology. In addition, the Optical Society in an earlier issue, April of 1962, had a list of terms and units. The terms that would be used by most of us are summarized in the accompanying table. Assume that we are using white light, which is the usual case and generally the easiest to measure. The most popular instrument for this purpose is the Macbeth illuminometer, which is calibrated in photometric or visual units; we could also use some kind of radiospectrometer, which would be calibrated in radiometric units. The Macbeth is calibrated in foot-candles, but modern scientific usage requires conversion to the metric system. This is fairly easy, because 1 foot-candle is equivalent to 1 lumen per square foot. In lumens per square meter, also called the lux, this becomes $(100/30.48)^2 = 10.76$ larger, or 1 lumen per square foot = 10.76 lumens per square meter. These are units of illuminance, intended to measure light incident on a surface or target.

The usual units of power and energy can also be used to measure light. If these units are used, it becomes measurement in the radiometric system, and incident power is irradiance which is expressed

in watts-cm⁻²; incident energy or exposure is joules-cm⁻² or watt-sec-cm⁻². These concepts are summarized in the accompanying table:

	Photometric Units	Radiometric Units
Power	lumens	watts
Energy	lumen-seconds or talbots	watt-seconds or joules
Power per unit area	lumens/m ²	watts/cm ² or watts/m ²
Energy per unit area	lumen-seconds/m ² or talbots/m ²	joules/cm ² or joules/m ²

Obviously, for conversion from photometric to radiometric units, it is more convenient if the area units are the same, e.g., watts-cm⁻² to lumen-cm⁻². The conversion can be made with precision only if the wavelength distribution is known. In an appropriate manner, for tungsten lamps only, it can be made by letting 1 watt-cm⁻² = 20 lumen-cm⁻². This value is for a one kilowatt lamp; for a hundred watt lamp, it would be closer to 15 lumens/watt.

The profusion of units is unfortunate, but it becomes even worse in considering sources of light. The radiated power must usually be given in power per unit area per unit solid angle. In the photometric system, this would be termed a luminance or luminous steradian with units of lumens-cm⁻²-steradian⁻¹. Radiometrically it would be radiance or radiant sterance, with units of watts-cm⁻²-steradian⁻¹.

An easier method of specifying the source is available with the photometric system, if the source is an extended one. The procedure is to use the Macbeth illuminometer, but to point it at the source,

instead of at the incident surface as is the usual procedure, and to take a reading from the scale of the Macbeth. This reading is normally expressed in units of foot-candles, but because it is of a source now, the concept of what is measured has changed to that of luminance, and the reading is referred to as one of "equivalent illuminance", with units of "equivalent foot-candles". Rather than use this awkward-sounding unit, another has been substituted, which is the "foot-lambert". If the equivalent foot-candle is converted to the "equivalent lumens/m²" or "equivalent lux", then the luminance unit is called either the "blondel" or the "apostilb".

Fortunately, for flash blindness studies, the target values are generally more important than the source concepts, and to that extent the necessity for luminance measurements is usually slight. It is also clear that as few units as possible should be used, so that easy comparison would be possible between experiments. English units should be discarded, and only the photometric or radiometric ones be used. My own preference is for the photometric system when white light is used. If other than white light is used, however, the concepts are usually expressed in terms of narrow spectral bands within which the power and energy show relatively little variation, and I prefer a radiometric system. All the units must be modified then, to include the wave length range, e.g., watts-cm⁻²-steradian⁻¹-Å⁻¹.

The impression which I received from listening to these papers was that with the use of a flash, i.e., short duration stimulation, a unit was implied which was neither generally discussed nor fully defined in any of the standard references. Thus, in the papers we have just heard, and in the general literature when short exposures are mentioned, they are referred to as so many lumen-seconds per cm².

There are others who talk about lumen-seconds per ft^2 and there are still others who say watt-seconds per cm^2 or watt-seconds per meter^2 . Before we discuss this implied unit, I think we have to make a basic distinction. It is elementary, but often we forget that there is a difference between power and energy. Power is energy per unit of time, and thus, when we talk about a short-term exposure in which lumen-seconds or watt-seconds appears, it is now energy and not power that is the concept. However, in the system that the Optical Society has recommended, there is no unit or symbol or general way of discussing this increasingly useful concept. Because it is in units of energy per unit area, it could be termed energy surface density. I don't think it makes too much difference which words are used, as long as a term is standardized. Radiant energy density has already been defined, but it is a three-dimensional concept. In the radiometric system, it can be called radiant energy surface density, with units of joules/m^2 . In photometric terms, it would be luminous energy surface density, with units of $\text{talbots}/\text{m}^2$.

Of course, what the units tell you is only what has occurred at the surface of the eye. From the report by Battista yesterday, it seems clear that the energy going into the eye may be a critical factor, that is, many of the curves seem to collapse upon one another when the term energy per unit area or energy surface density was used to describe the stimulus. Some of the variation here might disappear or be minimized if the size of the pupil were also taken into account. If you are talking about energy surface density, that is, energy per unit area, the total amount of energy going into the eye is then that value times the area of the pupil, whether you use an artificial pupil, or measure the actual pupil area. My own

feeling is that we should not go beyond including the pupil size into the measurement.

So far, I have restricted the discussion, except briefly, to "white" light. Obviously, when you use different wavelengths, the situation becomes more complex because you now must worry about the differential absorption of the different wavelengths in the eye. I'm not sure quite what sort of system to use. My own feeling is that it might be better to specify these units in radiometric terms. The difference naturally between the radiometric and the photometric units would be the effect that the particular wavelengths have on the eye. If radiometric units were used, all you have to do would be to multiply the energy by the pertinent constant, i.e., the luminosity factor. Perhaps it would be advisable in reporting results of a study to specify it both ways, that is, specify the stimulus in radiometric units and then put in whatever factors you used to convert it to photometric units. This would help, if after 5 or 10 years, you want to make a recalculation to determine whether or not your data fit a newly proposed theory.

Major Pitts

In reference to energy units, there exists a standard; I don't know whether that's a proper term or not, at least its what everyone in the military uses to define energy units. This was arrived at by DASA (Defense Atomic Support Agency) and I'm sure that there are DASA representatives here and we could get these copies from them. I didn't know this was coming up or I could have brought copies, in fact, if you look over my paper, you'll find that I had to rewrite the thing to fit their energy units. I'm rather curious about these

symbols since I think you could pick up any so called standard textbook and find that the symbols differ from the Physics and Chemistry Handbook. Another statement is this, any time you are going from radiometric terms to photometric terms, regardless whether you talk of white light, colored light or any other type of light, you must know the spectral distribution or you cannot make a calculation that is valid.

Dr. Sperling

May I also comment that you must not only know the spectral distribution in going from radiometric to photometric units and back, you must know the spectral sensitivity of the eye. This can be done readily if you use the standard CIE spectral sensitivity function. Some of us however, have shown this does not hold for all instances of the adaptive state of the eye. It varies in a rather extreme way so that I feel we're in something of a mess in attempting to go back and forth between radiometric and photometric units, since people dealing with vision literature tend to talk about retinal illuminance, and as Mrs. Miller showed us yesterday, there are some rather important relationships that hold when we talk about trolands, the unit of retinal illuminance. On the other hand, people concerned primarily with the physics of retinal burn effects, etc., use radiometric units. In order to define the continuum between the reversible visual effects and the irreversible burn effects, we must be able to either use the same units or be able to convert from one system to the other.

Mr. Derksen

I'm very glad that what was said has been said; some of it I was

going to say later. I heartily agree with you that we're in a mess, but I think we may be finding a way out of it after this discussion. I do want to endorse the idea of using radiometric units and reporting your spectrum. I think that this is the way out. One of the problems with using lumens is that whether we are interested in flash blindness in the scotopic spectrum or retinal burns, we are required to know the action spectrum in order to properly evaluate the energy which we have used to cause the effect. A problem I'm addressing myself to is an attempt to determine the presence of flash blindness or retinal burns from nuclear weapons sources. It would be very helpful if one has the radiometric terms and the spectral distribution but one does need the action spectrum and I saw some evidence of this being developed yesterday.

Mr. Promish

I'd like to take mild exception to something which I have seen cause confusion, at least in casual conversation, between one psychologist and another, and especially between one psychologist and one physicist, of which I am one. The confusion results from the casual bandying about of the words energy and power when used in photometry. As a physicist I must object to the use of the words energy and power when referring to photometric units. They should be kept for reference only to radiant units. If you want to talk about energy or luminous quantities, or luminous entities, you must think in terms of flux and flux rate and to divorce the words energy and power from photometry. When I want to go into radiant energy work, then I work with energy and power. There is confusion there and I think it should be cleared up. Now to go from entities to

quantities. From my experience in calculating, one trick we have used is to use the simple basic unit, not the milli, not the hecto, not the desi, but the simple watt, joule, lumen, or what have you, with the so called power of 10 notation in the numerical expression, thereby going from the beginning of the calculation to the end. If you then want to convert to milli, desi or nano units, you can, but I personally prefer to stick to the basic units and use powers of 10 in calculations. There is an operational need in the quantities and a semantic need in the entities in this field.

Dr. Hill

One of our primary problems is the relationship between time, t , and intensity, I , as far as the flash is concerned. We are also concerned primarily with vision and most vision laboratories have in them a Macbeth illuminometer as the standard basic instrument for measuring luminances of a particular target. At least the vision people I know agree that the Macbeth is more or less the basic instrument. It is very simple to use, and error is minimal with it. Now if you take a constant light source that can be shuttered and use this to generate a threshold, you now know what luminance a particular person requires in order to see, let's say, a 2 millisecond flash at a given level of acuity. With this, you know both figures, I and t . You know the duration of the flash and you know the luminance of the flash. With this you can now go to any other source, whether it's a flash tube or carbon arc lamp and come out with these same two figures. You can use an oscilloscope which is usually available in most vision labs and determine the time characteristics of the flash. Once you've obtained the acuity threshold, you know how

many filters or other attenuation you have had to put in the path of the source, and you can now compute it merely by putting these two sets of figures together. It's a very straightforward procedure, and is still the best way of calibrating a Maxwellian view. The primary reason for it is this; if you put a ground glass or some other diffuser at the focal point of a Maxwellian view, you can see your lamp filament. Surrounding it you can see a very bright region, then a progressively dimmer area. You cannot use an artificial pupil very well with a Maxwellian view, so you must include the size of the natural pupil in your calculations. You can use photography or perhaps densitometry, but this is extremely difficult. These procedures require tremendous amounts of equipment. If you find an acuity threshold with the eye in place under a given set of conditions, and equate that threshold with the measures which you have taken with an artificial pupil, given a constant source, you now know what stimulus you are presenting. I have done this both ways. I have used an EG&G radiometer to go through this whole exercise. At the present time I am doing this in order to show that these relationships ($I \times t$) hold all the way down to 60 microseconds for the acuity target. I used both the Macbeth and EG&G radiometer in order to come up with my luminances and durations. I recommend forgetting this business of taking radiometry measurements and doing the radiometric calculations. Instead, use the human as a null instrument.

Dr. Fry

I would like to point out that the terms we have been discussing are the new terms and I think at this stage, they are official for

this country, so that you'd better get used to these symbols. They come directly from the Optical Society and the Illuminating Engineering Society.

Dr. Sperling

I've been asked to discuss the studies of flash blindness using spectral light. On this program there were the papers by Capt. Randolph, by Dr. Jones and by Mr. Battista. Let me say a few words about why we want to know about the effects of spectral light. There are two main reasons for the Army; one, lasers are becoming quite significant as field devices and there is considerable concern about what effects they will have, and what means can be taken to protect against them; secondly, people often refer repeatedly to the match filter or interference filter or some spectral filter as a protective device against the flash of a nuclear weapon. The problem here is that if you are exposed to an intense spectral line source either directly or reflected from a surface, how long will it take you to recover to some criterion? Again, I'd like to point out my agreement with both Mrs. Miller and Dr. Hill that we should base our standards on acuity targets. I prefer the grating targets. In this regard the spectral case becomes quite complicated, since we have to measure the recovery not just for white light, but for the different wavelengths of light that might be used as narrow band sources on instrument panels. For white lights we should know the energy. However, the recovery to different wavelengths at different energies is more difficult to evaluate than white light. We would probably want to integrate the wavelength sensitivity of the eye at various stages of recovery with the energy distribution of whatever source

concerns us. Thus, we would have a very large matrix of data concerned with an extremely wide range of adapting or flash intensities, as well as quite a number of wavelengths of test light. How then do we go about obtaining such a large matrix of data? Mrs. Miller talked about the linearity of log time to recovery as a function of log troland-seconds of exposure, and indicated that there is a simple relationship between flash exposure and the steady state adapting condition or the so called increment-threshold measurement situation. I would conclude from her statements and her reference to studies done by Crawford and by Stiles and others, that we can greatly simplify this data collection task by doing increment-threshold studies. These are easier to do and require less data than conventional flash exposure and dark adaptation recovery studies. Recovery is then measured at representative wavelengths and these are then related to the dark adaptation function. This would verify the question of the linearity at different wavelengths and at a wide range of intensities. Now from what I saw of Dr. Battista's study for both the cone and rod portions, the recovery functions were linear with respect to log intensity. For Capt. Randolph's, which I think are largely rod data, this was also true. Some of the data from the program that I started and that Dr. Jones presented, attempts to cover this matrix of data for different wavelengths of the adaptation flash and different test or target wavelengths using the increment threshold steady state measurement technique. You saw some of the spectral sensitivity data that were derived in that program. Some interesting and I think explainable relationships resulted from those increment threshold studies. Let me just reiterate some of these; first as Jones

mentioned, the rhesus monkey is the subject of choice because we wanted to go up to very high intensities, hopefully those right up to the burn threshold to see what happens when you bleach very significant amounts of retinal pigment. The intensities have not been raised that high yet, but it will be done in the near future. Second, it was established by these studies that the spectral sensitivity function of the rhesus monkey is almost identical in shape with that of humans when tested in the same apparatus. The human and the rhesus curves almost superimpose each other on an absolute scale of reciprocal joules/cm². Using intense xenon arc lines as substitutes for lasers, since at that time we didn't have the lasers to cover the different parts of the spectrum, it was possible to fractionate the spectral sensitivity function. There was a white-light function which had the characteristic three peaks, one in the blue, one in the green, and one in the orange parts of the spectrum. This function changes radically with background luminance and spectral adaptation. Wald and Brown have shown that the dark adapted sensitivity function with a single peak at 550 nm in the yellow-green can be predicted as the arithmetic of the isolated cone response functions. We have just completed a study which relates the extreme condition of the dark adapted eye to the extreme condition of the highly light adapted eye. Thus, we found that with dark adaptation the three peak function gradually blended into the single smooth function that Brown and Wald had found. We believe this is related to a variable type of summation of the component function in which summation increases as the level of dark adaptation increases. Whether or not that is true, it is this type of general relationship between the flash and the steady state data such as that shown by Mrs. Miller's after image results and the

sensitivity function of the eye that will provide us with a mathematical model. Given this model, we could predict what would happen when a pilot's eye was exposed to a laser or an intense nuclear flash filtered by a wind screen or by some type of goggle. We could also predict how long it would take him to see the numbers on the dials in front of him or view a radar screen. I think we're making some progress toward this goal. I also think that we do have to iron out the problem of the use of units. Perhaps we should have a task force not only to recommend units, but of more importance, to make some conversions.

Dr. Hill

I have a couple of things which I think are problems which might well be looked into. With respect to the Chisum and Promish paper, I would have liked to have seen a plot of the response time as it relates to the edge of the adapting flash. In other words, the relation of the test target to the edge of the adapting flash. The reason I'm interested in this is because as far as atomic weapons are concerned, within the first 150 milliseconds, where the eye is protected by flash blindness protective devices, the size of the image in many, many cases is going to be extremely small. Under these circumstances it might be that we're going to end up training people to use other parts of the retina. The conditions in one of Mrs. Miller's papers that she didn't discuss, was for her smallest target. Now if I remember the paper correctly, the results were very variable under these conditions. This is indicative of one of the problems that we have to solve. What happens when you view a target that is extremely small, and how well can you see it? In other words, can we train the subject not to look with the light-adapted area of the eye but to look around the scotoma? As indicated by Dr. Severin's paper, pathological or physiological effects can be predicted on the basis of behavioral data much better than by a clinical diagnosis. For this reason I would like to see more studies of a possible behavioral criterion to measure the effects of retinal burns. There is some work going on in this area, but I believe more must be done. A second point is that although no one seems to like the term "flash blindness", everyone uses it. I feel somewhat guilty about it because I pushed this term when I first got into the business. I also said that this was a transitory effect while retinal burns were

a permanent effect. Well I no longer believe that either one of these deductions is acceptable. There is much evidence to show that all of the loss of vision from retinal burns is not permanent. A paper by Culver and his co-workers showed that retinal burn area decreased, and that the blindness due to the retinal burn decreases with time. We still do not know whether or not there is some long term retinal effect resulting from flashes in which there is no clinical evidence of a retinal burn. For my purposes I now use the term flash blindness to mean a decrement in visual effectiveness, for example, a decrement in visual acuity as measured by a behavioral or performance loss.

Dr. Fry

We have a short time left and I think we owe it to the organizers of the conference to summarize some of the contributions. I'm going to attempt to do this briefly and if we have a little time left over, we'll open it for discussion. There are a few questions I would like to ask so I hope we do have a little time left over for discussion.

One of the objectives of this conference was to explore the state of the art of the study of flash blindness at levels higher than we consider safe for work with humans and a little lower than the levels which would produce permanent impairment of the visual mechanisms. Mr. Battista presented one approach to this problem. As I understand it, he used ERGs produced by stimuli which covered a large area of the retina. This was for the purpose of avoiding the problem of stray light which will confuse the issue when you use small stimuli. This I think is a well accepted principle and was substantiated by the report of Dr. Armington. Now the one thing that strikes me about this, and I want Mr. Battista to talk to this point if he will, and

that is the principal effect you obtained under these circumstances was an effect in the cornea; at least this is apparently the first observable effect. This is exactly what you would expect when you have a broad extent for the stimulus, that is, it's well known for example, in the case of open furnaces where you have a large illuminated expanse that the damage produced will be in the cornea, and particularly in the lens of the eye. Specifically, cataracts are produced with little effect on the retina, since the energy is too well dispersed. This is contrasted to the case of the laser where you have the energies confined to just a point on the retina. This is the basis of photo-coagulation where the ophthalmologists repair retinas which have been separated from the choroid or pigment epithelium. I think it would be helpful if we could have an analysis of this problem in terms of concentrations of energy at the plane of the cornea, the plane of the entrance pupil, and at the plane of the retina. Mr. Battista indicated to me that if you go high enough you can also produce damage in the retina so his data I think would have some bearing on the overall problem about which most of us are concerned.

Mr. Battista

I must say that when we observed the corneal opacity, it was actually an observation which was really not part of the experiment. It only occurred at the high energy and the long duration flashes. This indicated that we had reached the upper limit of the energy or exposure conditions which we were trying to achieve. The corneal opacity indicated that we had reached the point of thermal coagulation of the corneal tissue and it was really not part of the experiment. We were not able to achieve this with the xenon flash lamp. Now I

would like also to say that when we observed corneal opacity at 12 watt sec cm^2 , opacities occurred in the rat as well as in the ground squirrel eye but if we doubled the energy level or tripled it, then we got destruction of the eye. That was fairly obvious because the eye lost its contour. I believe we got retinal involvement as well as corneal damage in those cases. A question was asked yesterday about whether or not with the arc we were getting a large amount of UV which might have given us the corneal opacity. Because of the lens system most of the UV was cut out. A further question was also asked this morning during the panel discussion as to whether the level of light adaptation might influence recovery after flashes. We have done this experiment in the rat, in a kitten, and in the ground squirrel and we could not determine any more rapid increase or decrease due to prolonged light adaptation of the animal. Recovery after a bright flash was about the same.

Dr. Fry

The second approach to the problem was the use of a training technique, exemplified by Capt. Randolph's contribution. I think it illustrates a great deal of patience on the part of anyone who is willing to undertake this and I think he's done an excellent job. I hope this can be carried through to the point where we produce retinal damage. The approach that he is using makes possible the production of retinal lesions independent of effects produced in the cornea and the lens of the eye. Another technique which was described here was Dr. Armington's approach in which he used an oscillating grating to elicit a response from the retina. This would be a fairly localized response and would, in my opinion, make an excellent

tool for studying retinal effects at the critical levels about which we are concerned. I hope that somebody will undertake a study of these critical levels, using that particular technique. I think there are complications with respect to this method such that we are not sure of what kind of response we are getting, that is to say, whether it is an on or off response. It is complicated because of the alteration of a pattern and you are getting the effect of the one stimulus superimposed on the opposite effect of the one that just preceded it. There are also meta-contrast effects involved in this type of situation which should be taken into consideration. This, however, is a matter of definition of the nature of the stimulus. I think it was adequately demonstrated that this technique represents a useful tool for the investigation of flash blindness effects.

Another approach to the problem is to avoid the generalized response to stray light of the retina as a whole. You have the same type of problem in connection with the pupil-area response which hasn't been discussed, but does represent an objective response to stimulation of the eye. I don't know why someone has not really explored it. It does suffer the same difficulty, that is, that you have a response to stray light obliterating or masking the effect to focal stimulation of the retina. One can avoid this problem using a recording of single cell units. Major Pitts described work at the level of the lateral geniculate body. The problem in this approach is that you have a number of these cells continuously firing anyway, and the effect of input from the retina is to modify the output of these single cell units. Although he didn't discuss it, it might be

well to consider restricting the measurements of the responses to those cells in the lateral geniculate body which respond to various luminance levels. Here you might get a graded response which should be helpful. Another short cut to the problem would be to go to the ganglion cell axons which you could do by going into the optic nerve fiber directly as has been done. It's a technique which is difficult and the electrophysiologists in this country have really not followed through on the early work done in England. You can get at the ganglion cells either at the retina or you can go to the lateral geniculate body and make certain that you are recording from the fibers coming into the lateral geniculate body. Criteria have been set up to determine whether you're in front of the synapse or behind the synapse at the level of the lateral geniculate body.

I think, therefore, that we've covered a sizable range of approaches to the overall problem of this, let's call it critical level. The second contribution of this conference to the state of the art comes in connection with studies of flash blindness and performance. We had a number of papers that bear on this general problem. The automobile night driving situation has been referred to by a number of investigators. Dr. Wolf pointed out that his studies were directed primarily to the solution of this problem. One of the things that I would like to comment about is that it seems to me that we're missing the boat on the problem of interpreting stray light in the eye.

One of the ways in which a high intensity, small flash can produce flash blindness is through atmospheric scattering and scattering

inside the eyeball which produces a gradient of illuminance on the retina surrounding the image of the glare source. This region of the retina covered by the gradient is subject to the same kind of adaptation process as the part of the retina covered by the image of the glare source. It is my belief that the state of the art has reached the point that we no longer have to study this problem by putting glare sources in the periphery of the field of view to bright adapt the foveal region of the retina. We can bright adapt the foveal region of the retina by exposing it to a large, uniform patch of luminance such as the 8° patch used by Mrs. Miller and then test how the visibility of various stimulus patterns applied to this region of the retina is affected during the recovery period.

The number of different kinds of distributions of glare sources in the field of view is infinite, but all of them mediate their effect by uniformly illuminating the foveal region. An enormous amount of labor can be saved by simply studying the effect of a patch of veiling of luminance on foveal vision.

In a practical situation such as driving at night against an oncoming train of cars with headlights, the situation is dynamic and complex, but with a Pritchard photometer equipped with a glare lens, one can assess the changes in stray light at the foveae to which the eyes are subjected and from this immediate past history of the stray light applied to the fovea one should be able to assess the state of adaptation. An "on the line" analogue computer is required to do this job. What is needed is a mathematical model of the processes of adaptation and the design of such a model seems to me to be the next major step in advancing the state of the art. Attempts in this direction have already been made.

In the paper by Chisum and Promish, much of the effort involving a peripheral glare source centered 6° or more from the test object could have been avoided by computing the veiling luminance at the fovea and then testing once-and-for-all the after-effect of a veiling patch upon a grating.

Wolf's study of the effect of age on glare presents a different kind of problem. Here the disability glare formula itself is at stake because as Wolf properly points out, the stray light varies with age and obviously the glare formula needs to be modified to make allowance for the effect of age on the amount of scatter. Although Wolf showed that disability glare increases with age, he did not design his experiment as Stiles and Holladay have designed theirs, namely, make it possible to assess the actual amount of stray light at the fovea.

A major contribution of the Chisum-Promish paper is that it brings into focus a different flash blindness problem. When the glare source is small in size ($1/2^\circ$) and forms an image centered at the same point on the retina as the 1° grating pattern used later for testing, the problem is no longer akin to superimposing a veiling patch, but we have to worry about the effect of the after-image of the glare source itself on the visibility of the grating. There appears to be no way of assessing this effect other than in terms of its effect on the subject's performance of his task.

It should be noted, however, that one condition they investigated was the effect of 12° glare source centered at the same point of the retina as the 1° grating test stimulus which was presented later. This phase of this work constitutes basic information about the after-effect.

The state of the art with respect to the interpretation of stray light effects would eliminate what you might call behavioristic studies. What I have in mind is illustrated by the Chisum and Fromish paper and also some of the work of Wolf. There are definite techniques which have been set up for evaluating stray light in the eye and two studies that bear specifically on this have avoided setting up the proper approach to getting information that will bear directly on the problem of stray light. In the first place, you might raise the point that we already have information about stray light and that it is no longer necessary to investigate it. We might concentrate on some other aspects of this problem, and I think I represent the thinking of the illuminating engineers. We have reached the stage now where we can devise a gadget which will measure effectively the stray light at the fovea in any given situation. This would enable us to avoid some unnecessary effort where stray light is involved.

Another point I wanted to discuss was the role of the positive after-image and this gets us into the problem of technology. One of the problems in connection with the positive after image is that Mrs. Miller's work involves high intensity, short duration stimuli. This produces a positive after-image which occurs immediately following the cessation of the stimulus. Now the typical positive after-image that most of us are familiar with comes in after a delay of 10-14 seconds and I'm very dubious about attributing the whole problem of performance or visibility following flashes, to the positive after-image. Now it's true that if you work at these high energy levels, it is a perfectly proper procedure. However, one is going to have complications, and Dr. Hill will point out that you're not interested in what happens 14 seconds later; you're interested in

what happens fractions of a second later. Now so far as technology is concerned, I think we are handicapped because we have high intensity short duration sources; we have steady sources of long duration but we haven't adequately covered the intermediate range. I don't believe anyone at this stage of the game knows how to make the comparison between positive after images generated in these two categories of stimuli. This is an area which I think needs further study. There is a possibility that this technological problem will affect the state of the art with respect to the reciprocity problem, and I know that Mrs. Miller has been very much interested in this relationship.

One of the other problems that we're interested in is the mechanisms of adaptation and we have had some confusion with regard to whether we're bleaching pigments or whether we're dealing with adaptation effects at a higher level, that is to say, neural effects. Certainly the neurophysiologists have demonstrated that there are some adaptation effects that do occur further along the visual pathway. Now one of the areas which I think has been ignored is at the photoreceptor level itself, that is, before you get down to what you can strictly call neural events. Selig, Hecht and others a long time ago talked about the primary visual response and the secondary visual response. We've had a great deal of clarification of the primary visual response through the research of Rushton and Wald and others in this general area, and this has thrown quite a different light on the nature of the secondary response. It appeared to me that in this secondary mechanism which I consider to be located at the level of the photoreceptors, one might well look for the basic,

short, high-speed adaptive processes rather than go further along the visual pathway. I throw this out as an area which I think needs further investigation.

There is the general problem of setting up models of flash blindness. Some people have already worked on this and have considered it as their ultimate objective. We have to be able to understand enough about ordinary adaptation phenomena and processes, including such things as pupil size and the positive after image, to build an adequate model with which we can make an assessment of the role of flash blindness in the performance of various visual tasks. I don't think that this conference has solved this problem but I hope it's called attention to the importance of holding a later conference directed toward a solution.

Conversion Factors for Flash Blindness Units

Willard L. Derksen

US Naval Applied Science Laboratory

Brooklyn, New York

<u>Source Brightness</u>	<u>x Conversion Factor</u>	<u>Retinal Illuminance</u>	
		<u>General</u>	<u>Specific</u>
Lamberts	$\frac{d_p^2 \times 10^4}{4}$	Trolands	9×10^4 tds
	$\frac{d_p^2 \pi e}{4 f e^2}$	lumens/cm ²	2.8×10^{-2} lum/cm ²
Millilamberts	$2.5 d_p^2$	Trolands	90 tds
	$2.5 d_p^2 \frac{\pi e}{f e^2}$	lumens/cm ²	2.8×10^{-5} lum/cm ²

d_p = diameter of pupil = 6 mm

πe = transmittance of eye = .9

$f e$ = focal length of eye = 17 mm

1 Troland = 3.1×10^{-7} lum/cm²

1 lumen/cm² = 3.2×10^6 tds

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